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Innovative Haptic-Based System for Upper Limb Rehabilitation in Visually Impaired Individuals: A Multilayer Approach

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Corresponding Author:	David Vallejo Universidad de Castilla-La Mancha Ciudad Real, Castilla-La Mancha SPAIN
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Universidad de Castilla-La Mancha
Corresponding Author's Secondary Institution:	
First Author:	Javier Albusac, PhD
First Author Secondary Information:	
Order of Authors:	Javier Albusac, PhD
	Vanesa Herrera, MsC
	Santiago Schez-Sobrino, PhD
	Rubén Grande, MsC
	Dorothy Monekosso, PhD
	David Vallejo, PhD
Order of Authors Secondary Information:	
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Innovative Haptic-Based System for Upper Limb Rehabilitation in Visually Impaired Individuals: A Multilayer Approach

Javier Albusac[1†], Vanesa Herrera[1†], Santiago Schez-Sobrino[1†], Rubén Grande[1†], Dorothy N. Monekosso[2†], David Vallejo[1*†]

[1*]Department of Information Technologies and Systems, University of Castilla-La Mancha, P. de la Universidad 4, Ciudad Real, 13071, Spain.
[2]Department of Computer Science, Durham University, Stockton Road, Durham, DH1 3LE, United Kingdom.

*Corresponding author(s). E-mail(s): David.Vallejo@uclm.es;
Contributing authors: JavierAlonso.Albusac@uclm.es; Vanesa.Herrera@uclm.es; Santiago.Sanchez@uclm.es; Ruben.Grande@uclm.es; Dorothy.Monekosso@durham.ac.uk;
†These authors contributed equally to this work.

Abstract

The integration of technology in healthcare has revolutionized physical rehabilitation of patients affected by neurological conditions, such as spinal cord injuries and strokes. However, a significant gap remains in addressing the needs of the visually impaired, as most current solutions are visually-centric. This paper presents a novel haptic-based system tailored for the visually impaired that aims to bridge this gap in upper limb rehabilitation. The system is underpinned by a multi-layer architecture that allows both patient guidance during rehabilitation and the definition and analysis of exercises by the therapist. The architecture design includes functionality to track the user's body by means of natural user interfaces, to register the user's movement, and to guide them through the vibrations of the haptic glove or through voice commands. Thus, the proposed solution empowers visually impaired individuals to perform therapist-defined hand exercises autonomously, fostering independence and optimizing therapeutic resources. The system captures detailed kinematic data, offering therapists a comprehensive insight into the patient's exercise execution. To assess the system's functionality, a pilot trial was conducted. This study also allowed us to compare the similarity of exercise performance under vibration-based guidance to the exercises defined by the therapist with that of verbal guidance. The results highlighted a significant increase in similarity to therapist-defined exercises when using the vibration-based guidance facilitated by the designed haptic glove.

Keywords: upper-limb rehabilitation, visual impairments, haptic feedback, vibration guidance, spinal cord injuries, stroke

1 Introduction

The fusion of diverse technologies across disciplines has expanded their reach, enabling innovative applications in unexpected sectors. This is evident in the realm of healthcare, where tools like robotics [1], wearable technology [2], and serious gaming platforms [3] have been repurposed to address a variety of physical and psychological conditions. A notable transformation is observed in the field of videogames and Virtual Reality (VR). Initially conceived for leisure, these platforms are now being used in sectors such as education, healthcare, and digital marketing. The increasing use of VR in medical rehabilitation indicates its effectiveness in addressing a range of neurological disorders, including autism, multiple sclerosis, cerebral strokes, and spinal cord injuries (SCI) [4, 5]. Physical rehabilitation refers to the continuous repetition of physical exercises of varying difficulty, tailored to the individual limitations of each patient. Particularly noteworthy is their impact on patients with SCI [6] and those recovering from cerebral strokes, underscoring the versatility and potential of these technological interventions [7].

Globally, SCI present a profound health concern, with incidence rates spanning from 13,019 to 163,420 per million individuals [8]. These injuries frequently result in severe consequences, such as reduced upper limb functionality, muscular atrophy, sensory loss, and heightened muscle tone or spasticity [9]. Given these challenges, rehabilitation emerges as a critical intervention, striving to restore muscle functionality and enhance the overall well-being of the affected individuals [10].

Stroke, another major global health issue, affects millions annually. According to the World Health Organization (WHO), stroke was the second leading cause of death worldwide, accounting for approximately 11% of all deaths. Furthermore, WHO estimates that globally, 13.7 million people experience a stroke each year, and 5.5 million of them die as a result1. Additionally, stroke is a leading cause of serious, long-term disability worldwide [11]. This reflects the impact of the issue, given that strokes not only cause various physical and cognitive challenges [12], but also heavily burden healthcare systems and families. Similar to SCI, strokes can leave lasting effects, often resulting in muscle weakness, coordination problems, speech impediments, and even visual disruptions. Rehabilitation for stroke survivors is a complex process that aims to improve physical capabilities, as well as address cognitive and sensory deficits [13]. Integrating technology into therapeutic regimens can be of great help for stroke survivors, as with SCI patients. This approach ensures that interventions are comprehensive and customized to meet each patient's specific needs, thereby enhancing the potential for recovery [6].

Despite technological advancements and integration in rehabilitation, a significant gap remains in addressing the needs of a particular demographic: the blind and visually impaired. Most current solutions, particularly those based on VR and gaming platforms, heavily rely on visual feedback. This visual-centric approach, while effective for the general population, renders these technologies largely inaccessible to those with visual impairments.

Several reasons contribute to this oversight. Firstly, the initial design and conception of these technologies were primarily for sighted individuals, with the primary mode of interaction and feedback being visual. As a result, the user interfaces, graphics, and other essential components are not designed to cater to those without sight. Secondly, there is a lack of awareness and understanding of the unique needs and challenges faced by the visually impaired community [14]. This often results in a one-size-fits-all approach, which, while well-intentioned, fails to address the specific requirements of this group. Moreover, the visually impaired population is diverse. The spectrum of visual impairment ranges from total blindness to various levels of partial sight, each presenting distinct obstacles and requirements. Designing technologies that cater to this wide range of needs requires a deep understanding of the user experience from their perspective.

Recognizing these challenges, there is a pressing need to shift from solely visual solutions to those that incorporate auditory and haptic feedback. Auditory solutions can provide essential cues and guidance, leveraging spatial sound and voice instructions to guide the user. On the other hand, haptic feedback, which involves tactile sensations, can offer real-time feedback through vibrations or other physical cues. Such multi-sensory approaches not only provide accessibility for visually impaired individuals but also improve the overall user experience, ensuring that rehabilitation is inclusive and effective for all.

Given the outlined challenges and the pressing need for inclusive rehabilitation solutions [15], this paper introduces a novel haptic-based system tailored for the visually impaired. The proposal integrates cutting-edge tracking technologies, with a particular emphasis on hand movements, into a specially crafted glove. This glove is equipped with an array of actuators capable of producing vibrations at different regions of the hand, providing immediate tactile feedback. Each vibrator, strategically placed on a part of the hand, marks the direction in which the patient should move the hand to follow a path similar to that defined by the therapist.

The primary aim of this solution is to facilitate upper limb rehabilitation. The underlying architecture has been designed to guide individuals who are visually impaired or have limited vision through the trajectories necessary for hand exercises, which are defined by therapists. This initiative is supported by two primary objectives. Firstly, we aim to empower patients with a sense of autonomy, allowing them to engage in rehabilitation exercises without the constant supervision of a therapist. This not only fosters independence but also optimizes therapeutic resources. Secondly, the system is designed to capture detailed kinematic data throughout the exercise sessions. These data include translations and rotations in three-dimensional space of the observed limb, encompassing a broad range of rehabilitation exercises.

Such data acquisition grants therapeutic specialists a granular insight into the patient's exercise execution, far beyond mere observation. With this data, therapists can conduct in-depth analyses of the patient's movements, enabling them to objectively assess the visually impaired patient's progress over time. In essence, this solution strives to enhance the rehabilitation experience for the visually impaired while equipping healthcare professionals with the tools to optimize therapeutic outcomes.

To validate the system's functionality, we conducted a pilot trial. The central focus of this trial was to assess how well the system aids in achieving a similarity in exercise execution between the patient and the therapist. This was done by comparing two distinct guidance scenarios: one facilitated by vibration-based feedback using the specially designed glove, and the other guided verbally by the system. Preliminary results from our study indicate that vibration-based guidance significantly outperforms verbal instructions, both in terms of precision and in the reduced time required to complete the exercises. Moreover, the haptic feedback provided by the glove not only enhances the accuracy of the exercise execution but also empowers visually impaired individuals to perform the exercises autonomously.

The rest of this paper is organized as follows. Section 2 discusses related works, paying special attention to research articles focused on physical rehabilitation for the visually impaired. In Section 3, we provide a detailed description of our proposal, including the system's architecture, the exercise definition, the haptic glove design, and the adopted vibration-based guidance method. Section 4 presents the experiment, providing details on the achieved results, discussing implications, and highlighting study limitations. Lastly, Section 5 concludes the paper, summarizing the key findings and contributions of this research.

2 Related work

Rehabilitation for the blind involves not only physical adaptations, but also significant psychological challenges [16]. The experience of blindness can lead to feelings of grief, loss of self-worth and the risk of depression and anxiety. Adaptation requires both the acquisition of new skills and the abandonment of old visual habits. An in-depth understanding of these issues is essential for effective rehabilitation planning. On the other hand, aesthetics also play a crucial role in the acceptance and use of assistive technology for visually impaired people because of the perceived stigma associated with such devices [17]. Many visually impaired people feel self-conscious about using devices that stand out or label them as different. Devices that are sleek and similar to mainstream products can reduce feelings of otherness and encourage wider use. Thus, the design of assistive technology must address both function and aesthetics to increase user adoption and social acceptance. A related review discussed a comprehensive analysis of published articles on navigation solutions for the visually impaired [18]. In particular, this review focused on primary solutions that can be used both indoors and outdoors, which were based on different technologies. The review shows that many navigation systems proposed for this population lack essential features that are crucial for autonomous navigation. A similar study, which particularly considers user-centered design and technological achievements is addressed in [14].

If we focus on the use of technological devices, the work presented by Manjari et al. introduced a comparative study that discusses the most relevant devices to provide support to visually blind [19], considering wearables and handheld devices especially. The analysis highlighted the prominent characteristics of these devices, considering aspects like power usage, weight, cost, and user-friendliness. The goal was to guide researchers in this domain, whether they aim to create a handheld device or devise an effective algorithm to promote independence, mobility, and safety for the visually impaired.

Another recent review, focused on spatial orientation and navigation technologies for the visually impaired, discussed how assistive technologies can be used to overcome mobility restrictions caused by visual impairment [20]. Particularly, this research work addressed, from a general point of view, how technology can identify a user's location, understand their relationship to the environment (context), produce navigation directions, and convey this information to the visually impaired user.

Researchers have also paid attention to identify significant obstacles faced by individuals with chronic conditions when obtaining and using assistive technology. In this sense, the work discussed by Howard et al. employed a method to determine whether these barriers persist across various chronic conditions [21]. Some of the research articles studied in this review are related to blind and visually impaired. A relevant example investigated the obstacles faced by visually impaired individuals in five southern Nigerian states when adopting assistive technologies [22]. The authors used a mixed-method approach, conducting qualitative interviews with 20 individuals and managing structured questionnaires to 423 participants aged 20 to 92.

Another recent study is based on the fact that smartphones and tablets come with inherent accessibility features and claims that their effect on the visually impaired community remains largely unexplored [23]. Thus, the authors delved into the adoption and usage of these devices among the visually impaired, examining how they might replace conventional visual aids and the factors that drive such choices. The study offers valuable insights for designers and rehabilitation professionals when understanding device usage.

On the other hand, the use of Electronic Travel Aids (ETAs) improve the mobility of people with visual impairments. However, designing an ETA that combines accurate object detection, effective alerts and ease of use is challenging. Some research works address this challenge [24]. For example, Jeong et al. developed an intuitive ETA that emphasizes reliable object detection and tactile feedback mechanisms for users [25]. The device incorporates seven ultrasonic sensors pointing in different directions to detect obstacles in the user's path. At the same time, tactile vibrators provide feedback on the position of obstacles. The system also features electromagnetic brakes, which are activated by the detection of an uneven surface and are connected to the rear wheels. The effectiveness of the newly developed ETA was tested in outdoor conditions with visually impaired participants, focusing on safety in ground drop-off scenarios. Recently, the development of affordable ETAs has become more and more relevant. Budrionis et al. presented a summary of recent research prototypes in the field of ETAs [26], which use smartphones to support orientation and navigation in indoor and outdoor environments by providing additional information about nearby objects.

Another relevant study introduces ALVU, a hands-free wearable designed for the visually impaired, enabling them to sense nearby obstacles and boundaries without physical contact [27]. The device consists of two main components: a sensor belt and a haptic strap. The belt, placed around the user's waist, features an array of time-of-flight sensors that use infrared pulses to measure distances to nearby objects or surfaces accurately. To relay this distance information, the haptic strap, worn around the upper abdomen, uses vibratory motors. These motors, in conjunction with a specially designed applicator, ensure distinct vibrations for user interpretation. Testing involved 162 trials with 12 visually impaired participants.

Another recent research paper described the NavCane, a novel electronic tool designed to facilitate autonomous navigation and orientation for visually impaired people [28]. A unique feature of the NavCane is its ability to provide prioritized obstacle information to the user, thus avoiding information saturation. This information is delivered through tactile and auditory channels. As a low-cost, low-power embedded obstacle detection and identification device, it provides an alternative to more complex machine vision systems. The prototype includes features such as a radio frequency identification reader, ultrasonic sensors, global communication and positioning modules, vibration motors, a gyroscope, a wet floor sensor and a battery.

Another interesting line of work, from which ideas can be drawn for the field of physical rehabilitation, is that adopted by some museums to enable blind people to experience works of art where the visual component is significant. For example, Cavazos-Quero et al. discussed a methodology in relation to the development of an interactive multi-modal guide prototype that uses both audio and tactile modalities to enhance the autonomous acquisition of information and appreciation of visual artworks [29]. The prototype includes a touch-sensitive 2.5D relief model of the artwork, which allows for unrestricted tactile exploration. Through specific touch gestures on this surface, users can retrieve localized verbal narratives accompanied by thematic background music, thereby enriching the auditory experience. A related work, discussed in [30], evaluated different patterns across different interfaces: three for speech, three for beeps and four for gestures. The aim was to identify the most competent and effective patterns for detecting, identifying and locating structures and objects in an unfamiliar environment. Ultimately, the goal was to help visually impaired users construct a cognitive representation of the explored area and perform tasks competently in the real environment.

Finally, we would like to highlight the existence of several commercial systems specifically designed for people with low vision. These systems have been designed from a general perspective to support daily activities, including physical and rehabilitation activities. Three of the most representative systems are IrisVision™[1], Orcam MyEye™[2] and eSight™[3].

[1] https://irisvision.com/irisvision-inspire/
[2] https://www.orcam.com/
[3] https://www.esighteyewear.com/

3 Proposal

3.1 Background

In previous studies, conducted in partnership with the Hospital Nacional de Parapléjicos de Toledo (Spain), we have developed VR solutions for upper limb rehabilitation in patients with SCI (see Figure 1). These studies highlight the benefits of using such technologies alongside traditional therapy [6, 31].

Our cloud-based platform offers a collection of customized, serious VR games that allow patients to simulate the movements and grasps performed in traditional therapeutic settings. These games are based on a common kernel that allows functional grasps (including the tenodesis grasp) to be recognized without the need for external controllers. This kernel also includes real-time kinematic data storage, which captures the patient's movements during sessions. This data provides the therapist with valuable information for feedback and personalized therapeutic adjustments, while also enabling the tracking of the patient's progress over time. Additionally, it helps identify whether the exercise is being performed correctly or if the patient is unintentionally making unwanted compensations or movements that may hinder the rehabilitation process. Unfortunately, as pointed out in Section 1, these VR methods are not suitable for those with visual impairments. However, we can draw on our previous experience in upper limb rehabilitation to propose the architectural design presented below.

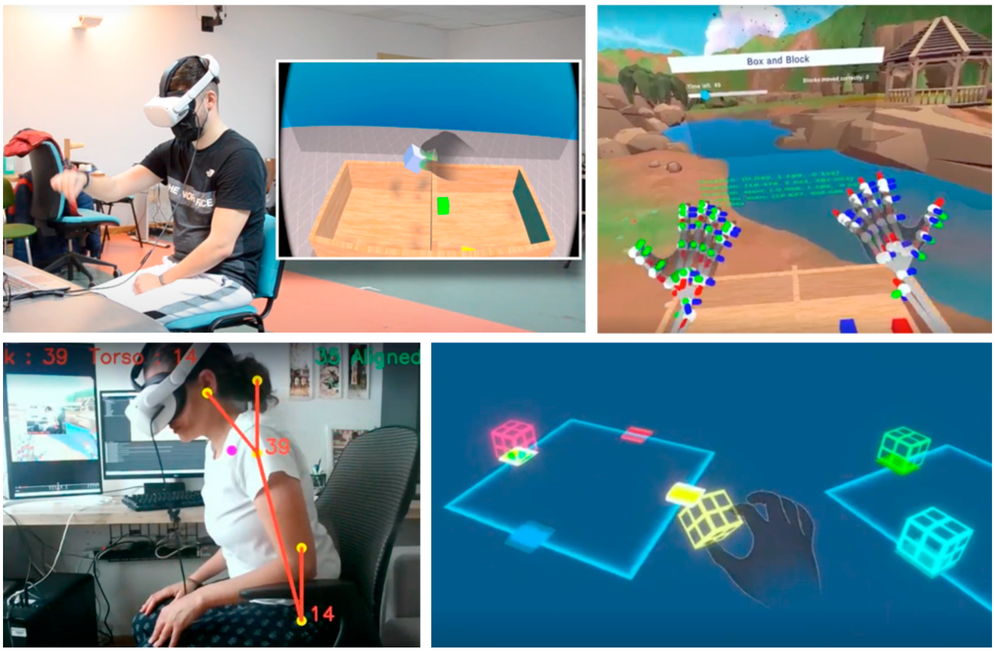

Fig. 1 Experimental sessions at the Hospital Nacional de Parapléjicos de Toledo during previous studies.

3.2 Architectural overview

Figure 2 graphically shows the proposed system's architecture. The design is structured into three major layers:

i) **Base Layer**. This foundational layer is dedicated to body tracking. An external tracking device, such as Azure Kinect DK, is used to capture the kinematics of the patient's skeleton. Then, the information is processed in an external PC and converted into vibration commands in the glove. The therapist also uses relies on the tracking device for the definition of exercises without using the glove. Instead, the system detects and records the trajectory associated with the rehabilitation movement defined by the therapist thanks to the data captured by the tracking device.

On the other hand, the backend component of this layer persistently stores the defined exercises and therapies. Plus, this layer is responsible for logging their execution. The access to this data is crucial as it allows therapists to analyze the progress of their patients over time, providing insights into the efficacy of the therapy and highlighting areas that may require further attention or modification.

ii) **Intermediate Layer**. The desktop applications for the patient and therapist are located in this layer. The patient's application features a dual-mode interface, which can be controlled through voice commands and by recognizing head and hand gestures. Additionally, this application includes a module to establish wireless connectivity with the haptic gloves, providing vibrational guidance to assist the patient

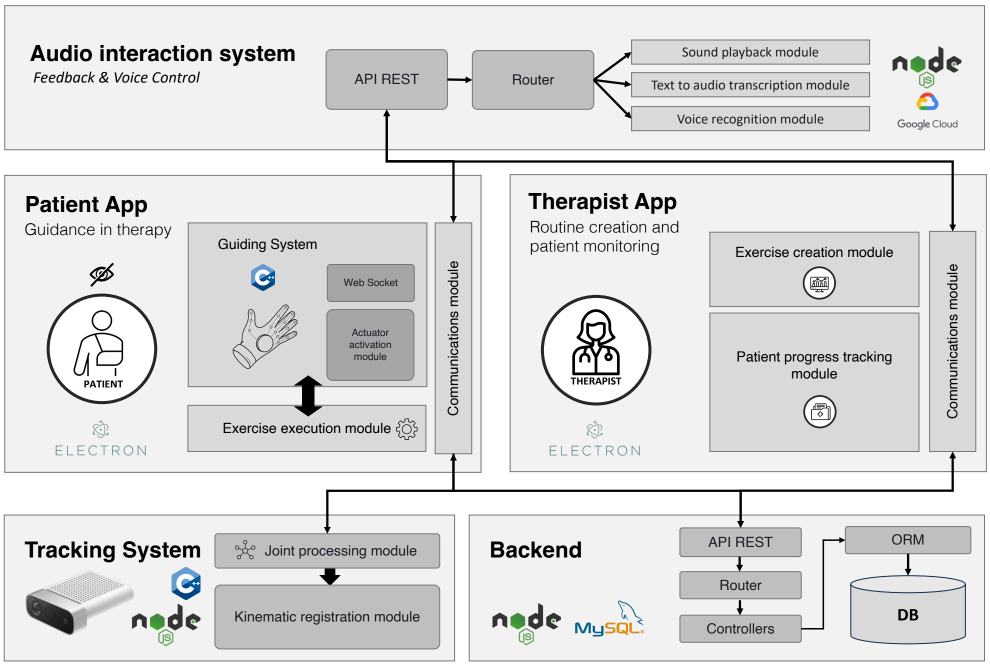

Fig. 2 General multi-layered architecture that underpins the proposed system.

during exercises. The exercise execution module allows patients to choose and participate in predetermined routines provided by therapists. The module continuously compares real-time tracking data to the predefined exercises. Any disparities from the established pattern, that is, from the reference standard defined by therapist, results in commands that activate specific vibrations to guide the patient back on track. Furthermore, the communication module is responsible for communicating with the base layer to ensure proper logging of data generated during the exercises.

Conversely, the therapist's application, while leveraging the same subsystems as the patient's application (namely, body tracking and data logging), is primarily oriented towards the creation of exercises and the monitoring of patient progress, with a focus on data analysis. Both applications are equipped with a communication module, ensuring seamless interaction with both the base and the subsequent layers. Analogous to the patient's application, the control logic of this layer operates on an external computer.

iii) **Top Layer**: Finally, this layer enriches the user experience by providing auditory feedback during exercise sessions. Additionally, it incorporates voice control capabilities, allowing users to navigate the system using voice commands.

AI-based Google Cloud technology is used for Text-to-Speech, and vice versa. The speech-to-text utility is employed for system control by blind people. Mainly, for the choice and execution of exercises. The recognition of voice commands has a direct effect on the system interface. On the other hand, the text-to-speech conversion is used in the experimentation sessions with verbal guidance. After hand tracking and the execution of algorithms that determine the similarity between movements and patterns, the appropriate corrections are estimated for the correct execution of the exercise. These corrections are translated into voice commands indicating the direction to follow (up, down, right and left).

3.3 Creation of exercises by the therapist

When defining rehabilitation exercises, the therapist plays a key role in our proposal. The workflow is as follows. The therapist positions themselves in front of the tracking device and performs the desired exercise, while it is being drawn on the screen (see Figure 3). This performance is recorded, capturing the hand's trajectory in a three-dimensional space at any given moment, denoted as $P(t)$. This position comprises the coordinates along the X, Y, and Z axes, represented as $X(t), Y(t)$, and $Z(t)$, respectively.

As the hand navigates through space, certain positions are earmarked for their significance in the movement trajectory. These are termed control points, with the i^{th} control point being represented as PC_i. To determine the extent of movement between these control points, a measure called the positional difference, $\Delta P(t)$, is employed. This measure calculates the difference between the current hand position and the last recorded control point.

To discern which movements are significant enough to warrant the recording of a new control point, a threshold value, θ, is set. If the hand's movement surpasses this

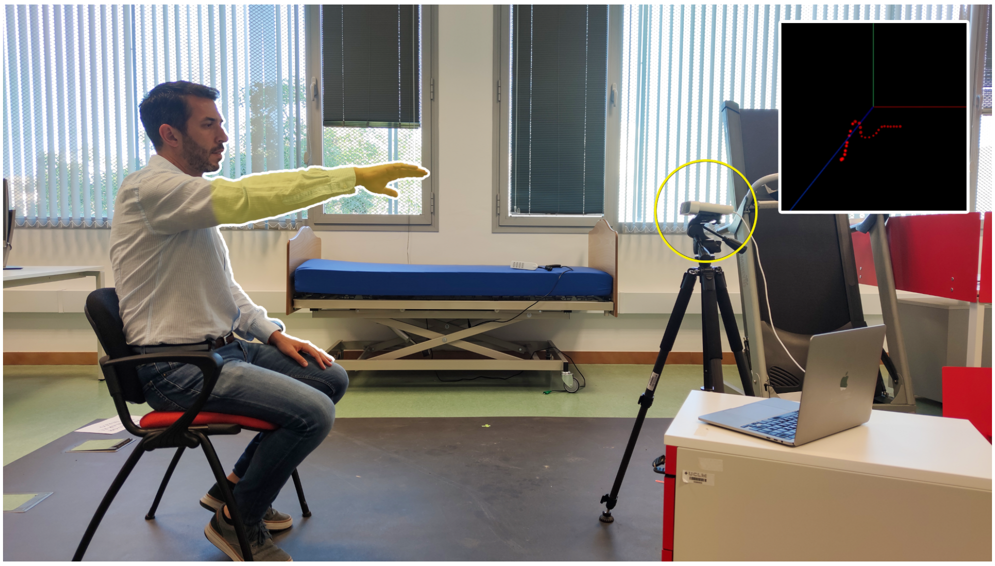

Fig. 3 Therapist defining an exercise and recreating the movement to be performed by the patients.

threshold in any direction (X, Y or Z), it is deemed significant. Each of these significant positions, or control points, is also associated with a timestamp, T_i, indicating the exact moment of its recording.

The entire process is initiated by the detection of a specific head gesture, signaling the start of the exercise recording. As the hand moves and the tracking device captures its trajectory, each frame, represented by t, is examined. The positional difference for each frame is computed, and if this difference exceeds the threshold values for any of the axes, a new control point, along with its timestamp, is recorded. The recording phase concludes upon the detection of a designated end gesture.

Next, a detailed formalization of the aforementioned process is presented.

3.3.1 Definitions

- $P(t)$: Hand position at time t in 3D space, represented as $P(t) = [X(t), Y(t), Z(t)]$.
- PC_i: The i^{th} control point.
- $\Delta P(t)$: Positional difference between the current point and the last control point.
- θ: Threshold value to determine if a movement is significant. The higher the threshold value, the greater the distance between the control points, and the smaller the quantity.
- T_i: Temporal reference of the i^{th} control point.

3.3.2 Algorithm

1. **Initialization:**
   - Set PC_0 as the initial position.

- Set $i = 0$.

2. **Recording Start:**
   - Wait until the start gesture is detected.
3. **Control Point Registration:**
   - For each frame t captured by the tracking device:
     - Compute $\Delta P(t) = P(t) - PC_i$.
     - If $|\Delta X(t)| > \theta$ or $|\Delta Y(t)| > \theta$ or $|\Delta Z(t)| > \theta$:
       * Increment i.
       * Set $PC_i = P(t)$.
       * Record T_i as the current timestamp.
4. **Termination:**
   - If the end gesture is detected, stop the recording.

3.3.3 Output

A sequence of control points $\{PC_0, PC_1, ..., PC_n\}$ with their corresponding temporal references $\{T_0, T_1, ..., T_n\}$ that define the exercise trajectory.

Along with the spatial data, therapists can provide additional numerical and textual descriptors to categorize the exercise. Nonetheless, within the context of the vibration guidance method, our primary focus remains on the spatio-temporal data. Upon definition, patients are afforded the opportunity to select the exercises they intend to perform (Section 4 shows some examples of defined exercises). The patient does not need to precisely replicate the therapist's movements, but rather navigate through specific control points, identified as crucial. These markers serve as milestones in the exercise trajectory, ensuring the patient follows the general trajectory specified by the therapist. These control points reflect the essence of the therapeutic exercise.

3.4 Glove design

The haptic gloves, as depicted in Figure 4.a, are equipped with two primary types of embedded devices: a) a microprocessor (see Figure 4.c) and b) Tecnoiot PWM vibration motors designed to produce vibrations (see Figure 4.d). To maintain a lightweight design and ensure user-friendliness, we intentionally omitted sensors such as accelerometers or gyroscopes. Instead, hand movement tracking is achieved using an external Azure Kinect DK device, which processes and captures real-time coordinates of the identified joints. The selection of this device is attributed to its high accuracy in body tracking. As discussed in [32], the standard deviation amounts to 17 mm, accompanied by a systematic error of $< 11mm + 0.1\%$ of the distance without multi-path interference.

The selected microcontroller for this design is the ESP8266, which boasts an integrated OLED display (illustrated in Figure 4.c). This choice was underpinned by the microcontroller's cost-effectiveness and compact size, allowing for seamless integration into the glove. Additionally, its built-in Wi-Fi module facilitates communication with

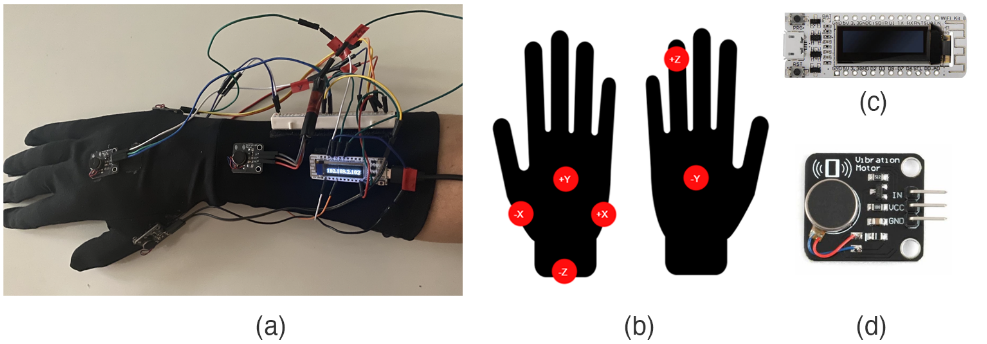

Fig. 4 a) Photograph of the gloves on the hand and arm of a patient. b) Location of the vibrators on different parts of the hand. The axis (X, Y, Z) in space where movement is expected is also indicated. c) micro-controller ESP8266 with an integrated OLED screen. d) Motor to produce vibration.

other system components. The inclusion of the microprocessor is necessary for transmitting activation and deactivation commands to the actuators, in this context, the vibrators.

Regarding hand movement, the patient's hand can traverse any of the three axes (X, Y, or Z) in either a positive or negative direction, following a therapist-defined pattern. This required the integration of six vibrators. The vibrational cues on specific hand regions indicate the direction in which the hand should move. Figure 4.b shows the vibrator placement and the corresponding expected axis of movement. As illustrated, vibrators facilitating movement along the X-axis are positioned on the lower sides of the hand. Those for the Y-axis are strategically placed on the palm and the back of the hand. Lastly, vibrators guiding movements along the Z-axis are located at the tip of the ring finger and the wrist.

3.5 Vibration guidance method

The movements of the therapist, which were pre-recorded, serve as a reference trajectory for the patient to follow. These predefined movements of the therapist are segmented into a series of control points, representing key positions in the exercise. As the patient performs the exercise in real-time, their movements are tracked and also segmented into control points. The essence of the guidance system lies in the calculation of the relative positional difference between the patient's current position and the expected position based on the therapist's pre-recorded movement. This difference, denoted as $\Delta P_{\mathrm{rel}}(t)$, is computed at each time instance t and provides a measure of how much the patient has deviated from the path charted by the therapist.

To provide real-time feedback, the system evaluates the magnitude of $\Delta P_{\mathrm{rel}}(t)$ along each of the three axes (X, Y, and Z). The axis with the largest deviation is identified, and haptic feedback is given to the patient in the corresponding direction. This feedback is designed to guide the patient back to the desired trajectory set by the therapist's pre-recorded movements. The process continues until the patient's movement is sufficiently close to the therapist's movement, as determined by a predefined threshold θ. If the patient's movement aligns well with the therapist's, both move on to the next control point. The exercise is deemed complete when all control points have been successfully navigated. A detailed formalization of this entire process is provided in the subsequent sections.

3.5.1 Definitions

- $P_{\text{therapist}}(t)$: Position of the therapist's hand at time t in 3D space.
- $P_{\text{patient}}(t)$: Position of the patient's hand at time t in 3D space.
- $PC_{\text{therapist},i}$: The i^{th} control point of the therapist.
- $PC_{\text{patient},j}$: The j^{th} control point of the patient.
- $\Delta P_{\text{rel}}(t)$: Relative positional difference between the patient's current point and the expected point based on the therapist's movement.
- θ: Threshold value to determine if the patient's movement is sufficiently close to the therapist's movement. The higher the threshold value, the more permissive the system. In other words, the system allows a greater difference from the pattern defined by the therapist.

3.5.2 Relative Positional Difference Calculation for Patient

The relative positional difference, denoted as $\Delta P_{\text{rel}}(t)$, represents the deviation of the patient's hand position from the expected trajectory during a therapeutic exercise at a given time t. It is computed by subtracting the sum of the patient's last achieved control point, $PC_{\text{patient},j}$, and the therapist's movement vector $\vec{V}$ between two consecutive control points, from the current position of the patient's hand, $P_{\text{patient}}(t)$:

$$\Delta P_{\text{rel}}(t) = P_{\text{patient}}(t) - (PC_{\text{patient},j} + (PC_{\text{therapist},i} - PC_{\text{therapist},i-1})) \tag{1}$$

where

- $P_{\text{patient}}(t)$: Current position of the patient's hand at time t.
- $PC_{\text{patient},j}$: Last control point reached by the patient, essentially the starting point for the current segment of the exercise.
- $\vec{V} = PC_{\text{therapist},i} - PC_{\text{therapist},i-1}$: Represents the movement $\vec{V}$ vector the therapist made between two consecutive control points, which is the movement the patient is expected to mimic.
- $PC_{\text{patient},j} + (PC_{\text{therapist},i} - PC_{\text{therapist},i-1})$: Gives the expected position of the patient if they followed the therapist's movement exactly, adjusted based on where the patient started the current exercise segment.

The equation $\Delta P_{\text{rel}}(t)$ provides a measure of how much the patient has deviated from the path the therapist charted, adjusting for the fact that the patient might not have started at the exact same position as the therapist. This is why the spatial analysis is performed in relative and not absolute terms.

3.5.3 Algorithm

1. **Initialization:**
   - Set $i = 1$ and $j = 1$ (starting with the first control point for both therapist and patient).
   - Detect the start gesture to begin the exercise.
2. **Relative Positional Difference Calculation:**
   - For each frame t captured by the Azure Kinect DK:
     - Compute the relative positional difference $\Delta P_{\text{rel}}(t)$ using the formula provided.
     - Determine the axis (X, Y, or Z) with the largest magnitude in $\Delta P_{\text{rel}}(t)$ and provide haptic feedback to the patient in the corresponding direction.

   Given the relative positional difference,

$$\Delta P_{\text{rel}}(t) = P_{\text{patient}}(t) - (PC_{\text{patient},j} + (PC_{\text{therapist},i} - PC_{\text{therapist},i-1})) \quad (2)$$

where

$$\Delta P_{\text{rel}}(t) = [\Delta X_{\text{rel}}(t), \Delta Y_{\text{rel}}(t), \Delta Z_{\text{rel}}(t)] \quad (3)$$

with

$$\Delta X_{\text{rel}}(t) = X_{\text{patient}}(t) - (X_{\text{patient},j} + (X_{\text{therapist},i} - X_{\text{therapist},i-1})) \quad (4)$$

$$\Delta Y_{\text{rel}}(t) = Y_{\text{patient}}(t) - (Y_{\text{patient},j} + (Y_{\text{therapist},i} - Y_{\text{therapist},i-1})) \quad (5)$$

$$\Delta Z_{\text{rel}}(t) = Z_{\text{patient}}(t) - (Z_{\text{patient},j} + (Z_{\text{therapist},i} - Z_{\text{therapist},i-1})) \quad (6)$$

3. **Guidance through Haptic Feedback:**
   - If the magnitude of $\Delta P_{\text{rel}}(t)$ is less than θ, increment i and j to move to the next control point.
   - Else, activate the vibrator corresponding to the axis with the largest magnitude in $\Delta P_{\text{rel}}(t)$ to guide the patient.
   - If i or j exceeds the number of control points, the exercise is completed.

   To determine the axis with the largest magnitude, the variable axis_{max} is defined as the value of axis that maximizes the magnitude of the relative difference $\Delta_{\text{rel, axis}}(t)$ for axis in the set $\{X, Y, Z\}$.

   Given

$$\Delta P_{\text{rel}}(t) = [\Delta X_{\text{rel}}(t), \Delta Y_{\text{rel}}(t), \Delta Z_{\text{rel}}(t)],$$

we compute the magnitudes of the components $\Delta P_{\text{rel}}(t)$ along each axis:

$$|\Delta X_{\text{rel}}(t)|, \quad |\Delta Y_{\text{rel}}(t)|, \quad |\Delta Z_{\text{rel}}(t)|.$$

Next, we determine the axis with the greatest magnitude of deviation:

$$\text{axis}_{\text{max}} = \arg \max_{\text{axis} \in \{X,Y,Z\}} |\Delta_{\text{rel, axis}}(t)|,$$

where $\Delta_{\text{rel, axis}}(t)$ is the axis component of $\Delta P_{\text{rel}}(t)$:

$$\Delta_{\text{rel, axis}}(t) = \begin{cases} \Delta X_{\text{rel}}(t) & \text{if axis} = X \\ \Delta Y_{\text{rel}}(t) & \text{if axis} = Y \\ \Delta Z_{\text{rel}}(t) & \text{if axis} = Z \end{cases}$$

Once axis_{max} is determined, we activate the vibrator corresponding to the axis with the greatest magnitude of deviation. For instance, if $\text{axis}_{\text{max}} = X$, we activate the X^- vibrator if $\Delta X_{\text{rel}}(t) > 0$ or the X^+ vibrator if $\Delta X_{\text{rel}}(t) < 0$. The same approach applies to the other axes and vibrators. Note that the vibrator on the opposite side of the largest displacement will always be activated. This is done to make the necessary correction and guide the hand back to the correct path.

This approach ensures that only the vibrator associated with the axis where the deviation is largest is activated, providing tactile feedback in the direction where the patient deviates the most from the desired trajectory. The rationale behind activating a single vibrator at a time stems from the need to avoid overwhelming or confusing the patient. Simultaneous activation of multiple vibrators can lead to ambiguity, making it challenging for the patient to discern the correct direction of adjustment. By focusing on a single axis of deviation and providing feedback solely in that direction, the patient can concentrate on making the necessary corrections without distraction. This targeted feedback not only simplifies the guidance but also enhances the patient's ability to understand and respond to the haptic cues, ensuring a more effective rehabilitation process.

4. **Termination condition**:

- If i or j exceeds the number of control points: The exercise is completed.

The patient receives auditory feedback when this event occurs. After the exercise is completed, the kinematics are stored and the system is available for new exercises.

4 Pilot trial

The main objective of the pilot trial is to preliminary assess the system's functionality. At the same time, we aim at analyzing the accuracy of the patients' movements by using the haptic glove, the similarity with the path defined by the therapist, and the comparison with a verbal guidance.

Ten healthy individuals (aged 17-53 years) participated in the experimental phase (a trial with patients is planned for later phases of the project, once we have validated the system works as expected). To simulate the conditions of a visually impaired patient, each participant's eyes were securely blindfolded to prevent them from seeing any visual cues during the exercise (see Figure 5). It is important to note that the

Fig. 5 Subject performing an exercise.

participants were not previously familiar with the trajectory they were expected to follow. By blindfolding the participants, we aimed to create a consistent experimental environment that closely mirrored the circumstances of a patient without vision. Table 1 provides a brief overview of the participants who took part in the experiment.

Subject	Gender	Age	Joint
Subject 1	Female	17	Right arm
Subject 2	Male	18	Left arm
Subject 3	Female	25	Left arm
Subject 4	Male	28	Right arm
Subject 5	Male	32	Right arm
Subject 6	Female	35	Right arm
Subject 7	Male	48	Left arm
Subject 8	Female	50	Right arm
Subject 9	Male	53	Right arm
Subject 10	Female	55	Right arm

Table 1 Description of the experiment subjects.

The core of our trial revolves around two exercises defined by a therapist. Each of the 10 participants was assigned to perform these exercises in two different conditions. Initially, participants executed the exercises with the aid of vibration-based guidance. Following this, they attempted to replicate the exercises without the vibrational cues. Instead, they depended on audio guidance from the system situated in the last layer of the architecture, which translated commands into basic auditory movement instructions such as “up”, “down”, “left”, “right”, “forward” and “backward”.

To evaluate and compare the effectiveness of the two guidance methods, we have chosen a set of parameters that provide quantitative insights into the participants' performance:

1. **Mean Path Deviation (MPD):**
   - This metric quantifies the average distance between the path taken by the participant and the ideal path as delineated by the therapist.
   - A lower MPD indicates a closer adherence to the prescribed path, signifying better precision in exercise execution.
2. **Number of Corrections:**
   - This parameter counts the instances where participants had to adjust their movement to realign with the ideal trajectory. If the patient's hand moves in a direction or orientation different from the next control point, then a corrective action is needed. Any movement that adjusts the hand's direction and orientation, guiding it towards the next control point, is counted in this parameter.
   - Fewer corrections suggest that the guidance method was more effective in keeping the participant on the correct path.
3. **Total Exercise Duration:**
   - This metric measures the time taken by the participant to complete the exercise.
   - A shorter duration might indicate that the guidance method was more intuitive or easier for the participant to follow. The time also depends on the complexity of the exercise.
4. **Significant deviations:**
   - This parameter counts the total number of significant deviations from the ideal path.
   - An error is defined as a deviation that exceeds a predefined threshold. Fewer errors indicate better adherence to the ideal trajectory and, by extension, a more effective guidance method. An error like this leads to spending more time completing the exercise and and increased difficulty in reaching the control points.

By analyzing the data obtained from these parameters, we aim to draw informed conclusions about the relative effectiveness of vibration-based guidance versus verbal instruction. This will provide valuable insights into designing more efficient and user-friendly guidance systems for therapeutic exercises in the future.

4.1 Exercise 1

Figure 6 displays the definition of Exercise 1. This is a relatively simple exercise involving an upward arm movement, a shift to the right, and finally a downward motion to return it to a position similar to the starting point. The figure also presents, in the middle section, an example of performing this exercise with vibration guidance, and on the right, an example with verbal guidance.

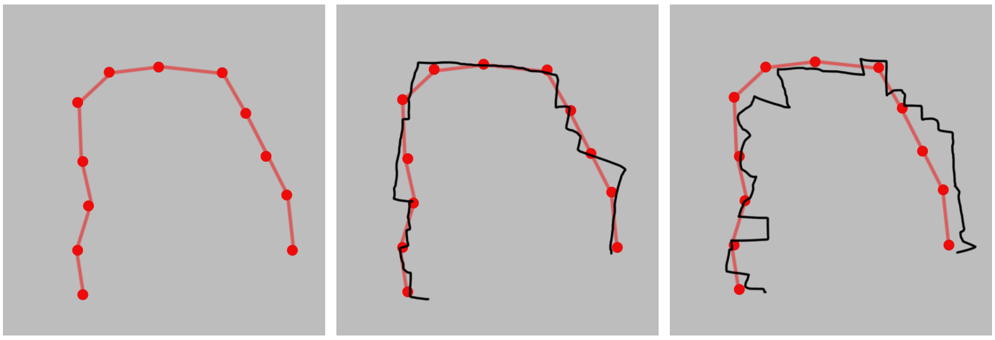

Fig. 6 From left to right: i) definition of exercise 1, ii) example of the exercise 1 with vibration guidance, and iii) example of the exercise 1 with verbal guidance.

Upon initial observation, it is evident that the trajectory followed with vibration guidance more accurately adheres to the path delineated by the therapist. Furthermore, not only are fewer corrections required compared to verbal guidance, but these corrections are also of a lesser magnitude.

Table 2 summarizes the results obtained during exercise 1 by the 10 individuals who were part of the experiment. The table provides insights into the performance metrics of subjects during Exercise 1. The Mean Path Deviation (MPD) across all subjects averages at 6.31 cm, signifying their typical deviation from the therapist's intended path. Concurrently, subjects required an average of about 5.3 corrections, suggesting that participants typically deviated from the intended trajectory slightly more than five times throughout their performance. The average duration taken by subjects to conclude the exercise hovered around 104.8 seconds. Additionally, the data indicates that, on average, participants encountered approximately two significant deviations from the prescribed path during their performance.

Subject ID	MPD (cm)	Number of Corrections	Total Duration (s)	S.Deviations
1	4.82	3	92	1
2	5.85	5	95	2
3	4.21	4	84	1
4	6.32	5	102	2
5	4.83	3	88	1
6	8.21	8	130	3
7	7.15	7	119	3
8	6.85	5	109	2
9	7.01	6	107	2
10	7.89	7	122	3

Table 2 Results with Vibration Guidance in Exercise 1

On the other hand, Table 3 shows the results for the same exercise but with a verbal guide. Upon comparing the results from Table 2, which presents data from the exercise with vibration guidance, to those from Table 3, which showcases results from the same exercise but with verbal guidance, several distinctions emerge. The average MPD for participants using verbal guidance is 10.46 cm, which is notably higher than the 6.31 cm observed with vibration guidance. This suggests a greater average deviation from the therapist's intended path when using verbal cues. Additionally, participants under verbal guidance required an average of 11.8 corrections, compared to the 5.3 corrections observed with vibration guidance, indicating more frequent deviations from the intended trajectory. The average total duration for completion was also longer with verbal guidance 138.3 seconds, compared to the 104.8 seconds with vibration guidance. Lastly, the average number of significant deviations was higher in the verbal guidance group, with a value of 6, compared to the 2 observed with vibration guidance. Overall, the data suggests that vibration guidance may offer a more precise and efficient method for this exercise compared to verbal guidance.

Subject ID	MPD (cm)	Number of Corrections	Total Duration (s)	S. Deviations
1	7.34	6	135	3
2	9.55	11	148	6
3	8.01	7	123	4
4	11.32	12	102	6
5	9.02	12	132	6
6	13.82	16	153	8
7	11.45	14	142	7
8	12.11	15	139	8
9	10.32	11	145	6
10	11.66	14	156	6

Table 3 Results with Verbal Guidance in Exercise 1

4.2 Exercise 2

Figure 7 presents the second exercise that has been defined and included in the trial. As with the previous exercise, it illustrates an example of the exercise being performed with vibration guidance (in the central section) and with verbal guidance (on the right side). This exercise has a more complex path, and even at a quick glance, one can notice a clearer accuracy in the execution when using vibration guidance as compared to verbal guidance.

Table 4 presents the results for the second exercise performed with vibration guidance. The average Mean Path Deviation (MPD) across all subjects is 8.08 cm, indicating the typical deviation from the therapist's intended path during this exercise. Subjects, on average, required about 10.5 corrections, suggesting that they deviated from the intended path slightly more than ten times during their performance. The average time taken to complete the exercise was 163.6 seconds. Furthermore, the data indicates that participants had, on average, between three and four significant deviations from the intended path during their execution of the exercise.

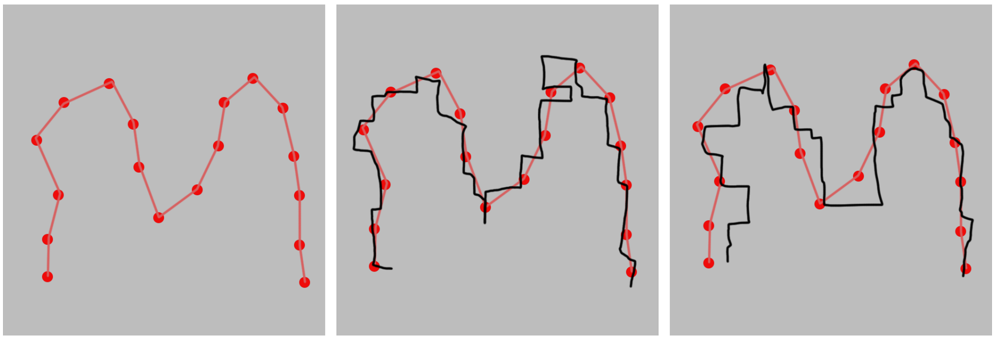

Fig. 7 From left to right: i) definition of exercise 2, ii) example of the exercise 2 with vibration guidance, and iii) example of the exercise 2 with verbal guidance.

Subject ID	MPD (cm)	Number of Corrections	Total Duration (s)	S. Deviations
1	5.67	6	157	2
2	6.45	9	165	3
3	6.67	8	148	3
4	8.32	11	185	4
5	6.14	7	162	2
6	9.75	13	159	5
7	8.66	11	142	4
8	8.33	11	180	3
9	10.56	15	173	6
10	10.34	14	165	5

Table 4 Results with Vibration Guidance in Exercise 2

Upon examining the results from Table 5 for the second exercise performed with verbal guidance, and comparing them with the results from Table 4 which used vibration guidance, several distinctions emerge. The average Mean Path Deviation (MPD) for participants in Table 5 is 11.78 cm, which is moderately higher than the 8.08 cm observed in Table 4. This indicates a greater deviation from the therapist's intended path when participants relied on verbal cues. Moreover, participants required an average of about 22.4 corrections with verbal guidance, a significant increase from the 10.4 corrections observed with vibration guidance. The average duration to complete the exercise under verbal guidance was approximately 243 seconds, substantially longer than the 163.6 seconds recorded with vibration guidance. Additionally, participants averaged about 7.2 significant deviations from the intended path in Table 5, compared to the 3.7 deviations in Table 4.

Finally, Table 6 illustrates the mean deviation between the trajectory followed by the patient and that set by the therapist, disaggregated by individual axes for each of the four experimental scenarios. It is evident from the data that the deviation is more pronounced in the Z-axis compared to the other two axes, in the case of vibration guidance. This observed discrepancy might be attributed to the placement of the

Subject ID	MPD (cm)	Number of Corrections	Total Duration (s)	S. Deviations
1	8.37	9	231	3
2	11.14	16	243	5
3	10.33	17	238	5
4	13.24	28	240	9
5	10.67	19	162	6
6	14.23	33	259	10
7	13.29	29	242	10
8	13.01	27	260	9
9	11.95	24	253	8
10	11.56	22	243	7

Table 5 Results with Verbal Guidance in Exercise 2

vibrators for these axes on the hand. Based on these results, the vibrators designated for these axes may be less intuitive than those for the other axes.

Guidance	X Dev. (cm)	Y Dev. (cm)	Z Dev. (cm)
Vibration (Ex. 1)	1.79	1.99	2.52
Verbal (Ex. 1)	3.28	3.68	3.50
Vibration (Ex. 2)	2.10	2.34	3.63
Verbal (Ex. 2)	3.99	3.79	4.00

Table 6 Avg. Axis-wise Deviation for Each Experimental Condition

4.3 Discussion

The rehabilitation exercises, as presented in the results, were designed to evaluate the efficacy of two distinct guidance methods: vibration (Figure 10) and verbal (Figure 11). The Mean Path Deviation (MPD), number of corrections, total duration, and significant deviations were the primary metrics used to gauge the performance of subjects under each guidance method.

Mean Path Deviation (MPD): The MPD serves as a measure of how closely a subject's movement aligns with the therapist's prescribed path. A lower MPD indicates better precision and adherence to the intended trajectory. From the data, it's evident that the vibration guidance consistently resulted in a lower MPD compared to verbal guidance across both exercises. Specifically, the average MPD for vibration guidance was 6.31 cm and 8.09 cm for Exercises 1 and 2, respectively. In contrast, the verbal guidance yielded average MPDs of 10.46 cm and 11.78 cm for the same exercises. This suggests that subjects were able to more accurately replicate the therapist's movements when guided by vibrations. Figure 8 provides a comparative overview of the average MPD results across the four scenarios.

Number of Corrections: As previously stated, this metric provides insight into the number of times a subject deviated from the intended path and had to adjust their movement. Fewer corrections indicate a more intuitive or effective guidance method. The vibration guidance method consistently required fewer corrections than the verbal

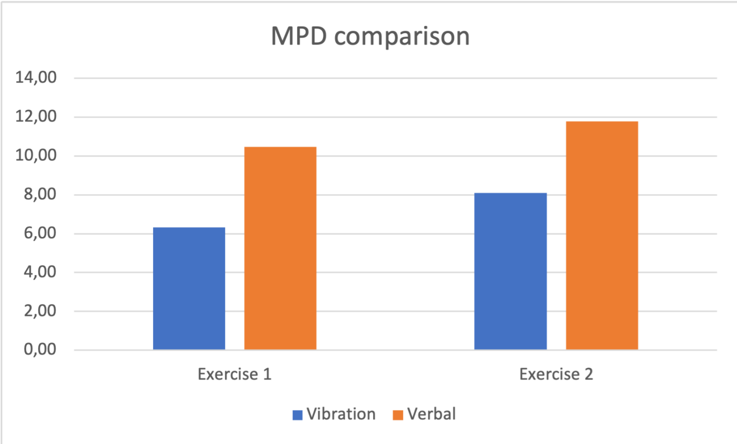

Fig. 8 MPD comparison.

guidance in both exercises, reinforcing the notion that vibration guidance offers a more straightforward and intuitive path for subjects to follow.

Moreover, the results also reveal a pronounced positive correlation between MPD and the number of corrections across all datasets. As the MPD increases, there is a corresponding rise in the number of corrections made. Specifically, for the vibration guidance in the first exercise, the correlation coefficient stands at 0.85, denoting a robust positive relationship. This correlation slightly diminishes for the verbal guidance in the same exercise, with a value of 0.78. In the context of the second exercise, the correlation remains substantial for both guidance methods, with values of 0.82 for vibration guidance and 0.75 for verbal guidance. These findings suggest that regardless of the guidance method or the specific exercise, as participants deviate further from the ideal path, they tend to make more corrective actions.

In Figure 9, this relationship between MPD and the number of corrections is visually represented through scatter plots. Each plot in the mosaic distinctly captures the correlation for a specific guidance method and exercise combination. The trend lines in these plots further emphasize the positive association between the two variables, providing a clear visual confirmation of the statistical findings discussed earlier.

Total Exercise Duration: The time taken to complete each exercise can be an indirect measure of the guidance method's intuitiveness. While there were variations among individual subjects, on average, the vibration guidance method resulted in slightly shorter completion times.

Significant Deviations: These are deviations that notably stray from the intended path. A lower count indicates better adherence to the therapist's trajectory. Once again, vibration guidance outperformed verbal guidance in minimizing these significant deviations.

In conclusion, the vibration guidance method consistently outperformed the verbal guidance method across all metrics and exercises. The data suggests that haptic feedback, in the form of vibrations, provides a more effective and intuitive means for subjects to replicate prescribed movements in rehabilitation exercises. This has implications for the design of future rehabilitation protocols, especially for populations where visual or auditory cues might be less effective.

4.4 Limitations of the study

One of the primary constraints of our study pertains to the relatively small number of participants involved. While the data gathered provides insightful observations, the limited sample size may not be representative of the broader population. This constraint makes it challenging to extrapolate our findings to a more general context.

Moreover, the study was conducted using healthy individuals. Even though their vision was suppressed during the experiments, these participants did not possess any inherent mobility challenges. This experimental setup might not capture the intricacies and challenges faced by individuals with genuine mobility impairments or other health complications. Consequently, the results, when applied to a population with specific therapeutic needs, might exhibit variations.

Recognizing these limitations, we have charted out plans for future research endeavors. There is an intention to conduct further experimentation with an expanded group of subjects to solidify our findings. Additionally, subsequent phases of the project are slated to involve patients, ensuring that the proposed methods undergo rigorous testing in therapeutic scenarios.

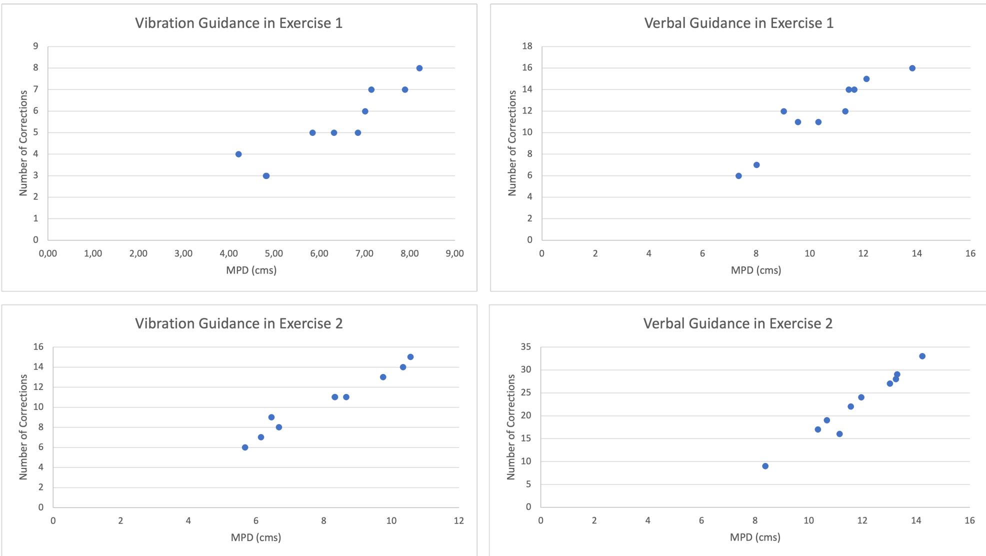

Fig. 9 Relationship between MPD and the Number of Corrections across the four experimental conditions. Each plot represents a distinct guidance method and exercise combination, highlighting the correlation between the two variables.

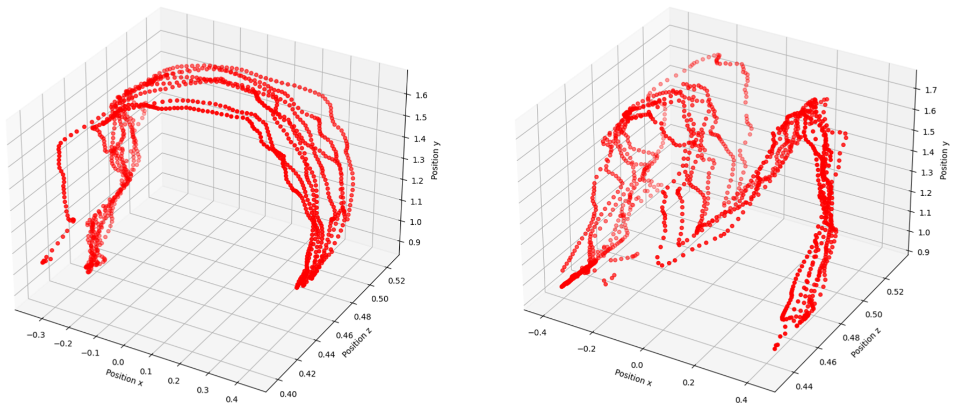

Fig. 10 Three-dimensional visualization of vibration guidance exercises one and two as performed by the participants in the study.

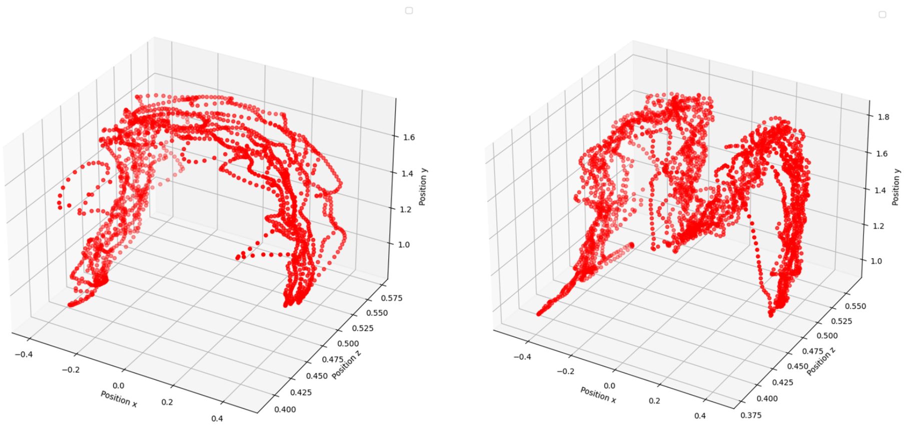

Fig. 11 Three-dimensional visualization of verbal guidance exercises one and two as performed by the participants in the study.

5 Conclusions

In this work, we have presented a novel haptic-based upper limb rehabilitation system for people who are blind or have significant visual impairments. The integration of a customized glove allows the generation of vibrations that guide the user in the performance of rehabilitation exercises based on the similarity of their performance to that of their therapist in three-dimensional space. At the same time, thanks to a precise tracking system, the system is able to capture kinematic data for further analysis and monitoring. The system is based on a multi-layer architecture divided into different functional modules, which facilitates its extensibility and promotes its scalability. In this sense, the therapist can define new rehabilitation exercises through a natural user interface, taking into account a set of control points that are used to manage the automatic guidance of the user (through vibrations in the glove or through voice commands).

The system was evaluated for functionality by ten healthy, appropriately bandaged individuals who performed two different rehabilitation exercises. These exercises were performed with the haptic glove integrated in the system, thus benefiting from the vibration guidance, and without the glove, receiving instructions through voice commands to guide the user's movement. The paper also presents a preliminary quantitative evaluation of these two methods, which has allowed us to draw initial conclusions about the relative effectiveness of vibration-based guidance versus verbal instruction. In essence, the vibration guidance method consistently outperformed the verbal guidance method across all metrics and exercises. Mean Path Deviation (MPD) and number of corrections, both critical metrics in our evaluation, showed that participants were more likely to follow the therapist-defined path when guided by vibration.

However, it is important to contextualize these findings within the limitations of the study. The research was conducted with a limited number of healthy participants, which may not fully capture the complexity of therapeutic scenarios involving patients with mobility impairments. Despite these limitations, the promising results of this preliminary study provide a solid foundation for future research.

In particular, we will focus on three specific areas. First, we will improve aspects related to the hardware component of the system. To this end, we intend to improve the design of the haptic glove so that it is as user-friendly as possible, and we will consider upgrading the tracking module so that it is not necessary to have a specific hardware device to track the user's joints. In this sense, we will explore software-only solutions such as the open source MediaPipe PosePipe library[4]. Secondly, we will evaluate the integration of gamification mechanics to incentivize the patient's continued use of the system. In other autonomous rehabilitation projects we are working on, the incorporation of these techniques has been highly valued by users. In particular, we are investigating the integration of rehabilitation exercises that are as similar as possible to everyday actions. Finally, another interesting line of future work relates to the ability of the system to automatically modify the exercise routines assigned to a patient according to his or her level of progress and particular condition. This would allow for more effective and personalized rehabilitation.

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Data availability

Existing datasets will be made available on request.

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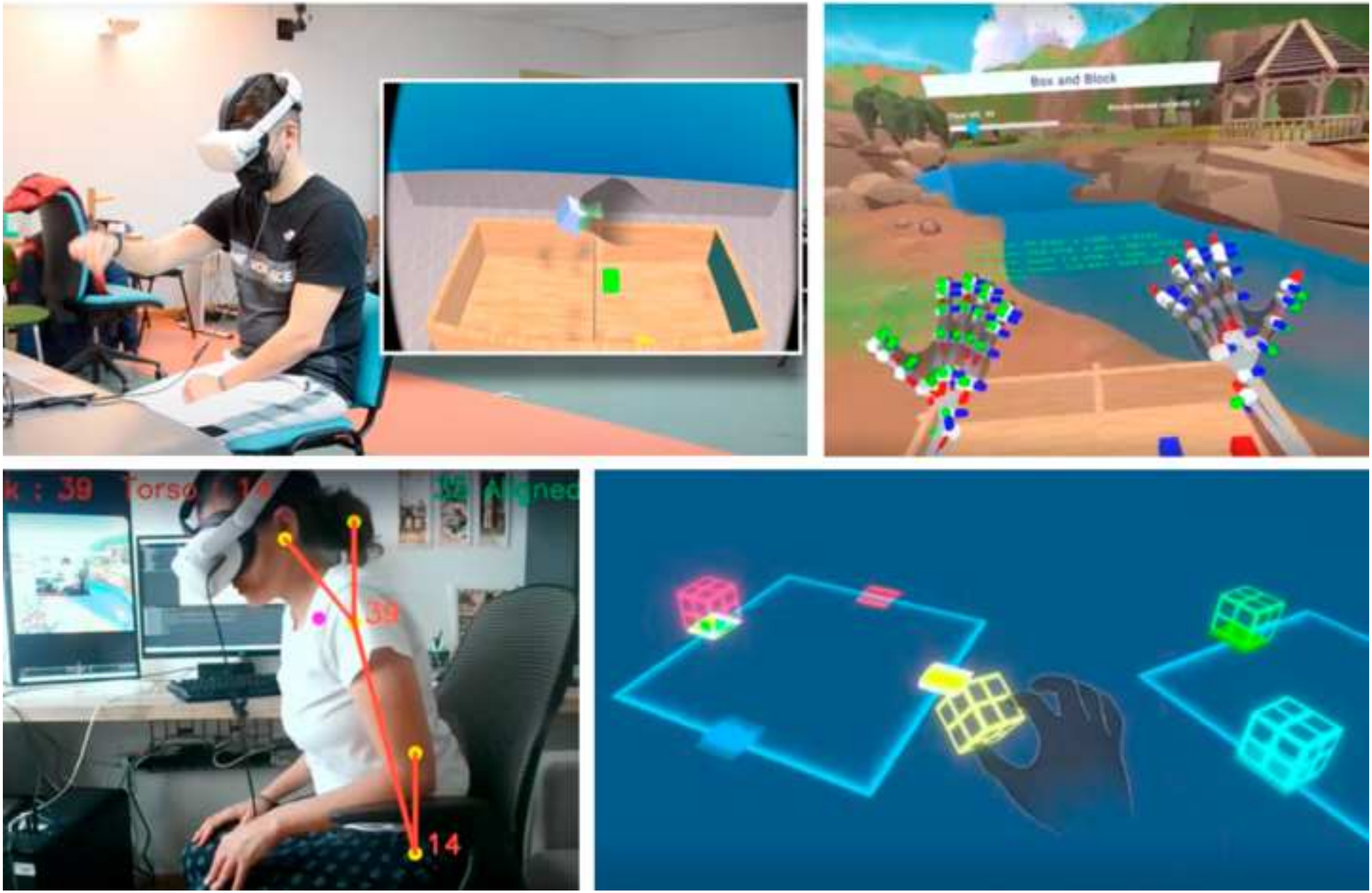

Figure 2

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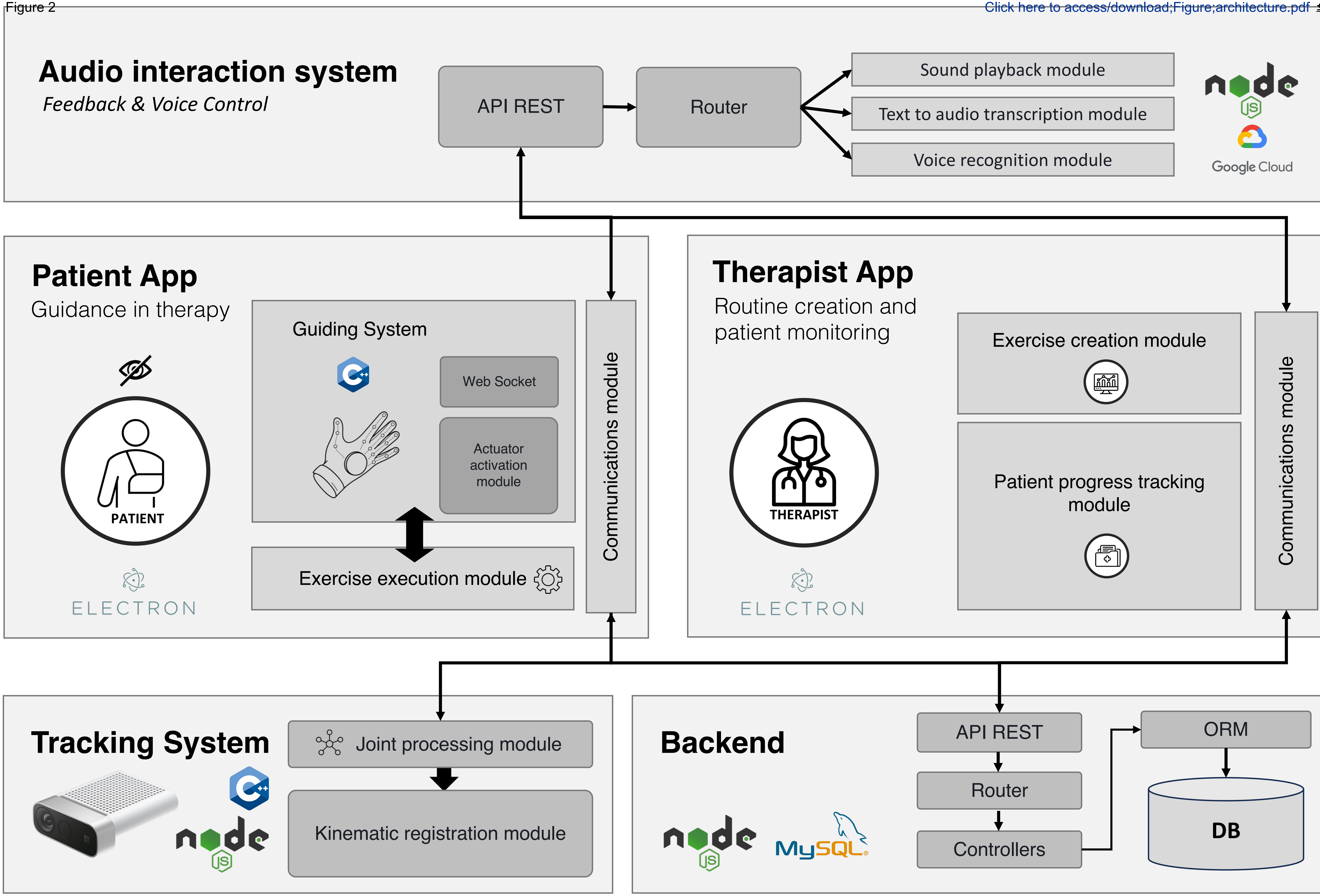

Figure 3

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Figure 4

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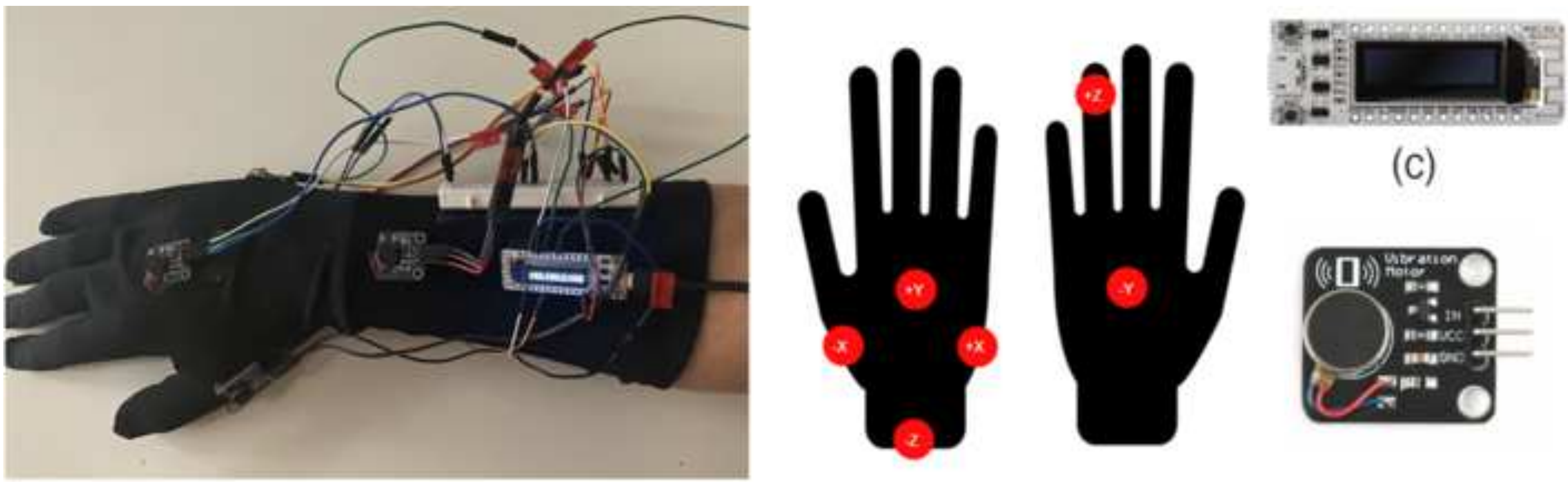

(a) (b) (c) (d)

Figure 5

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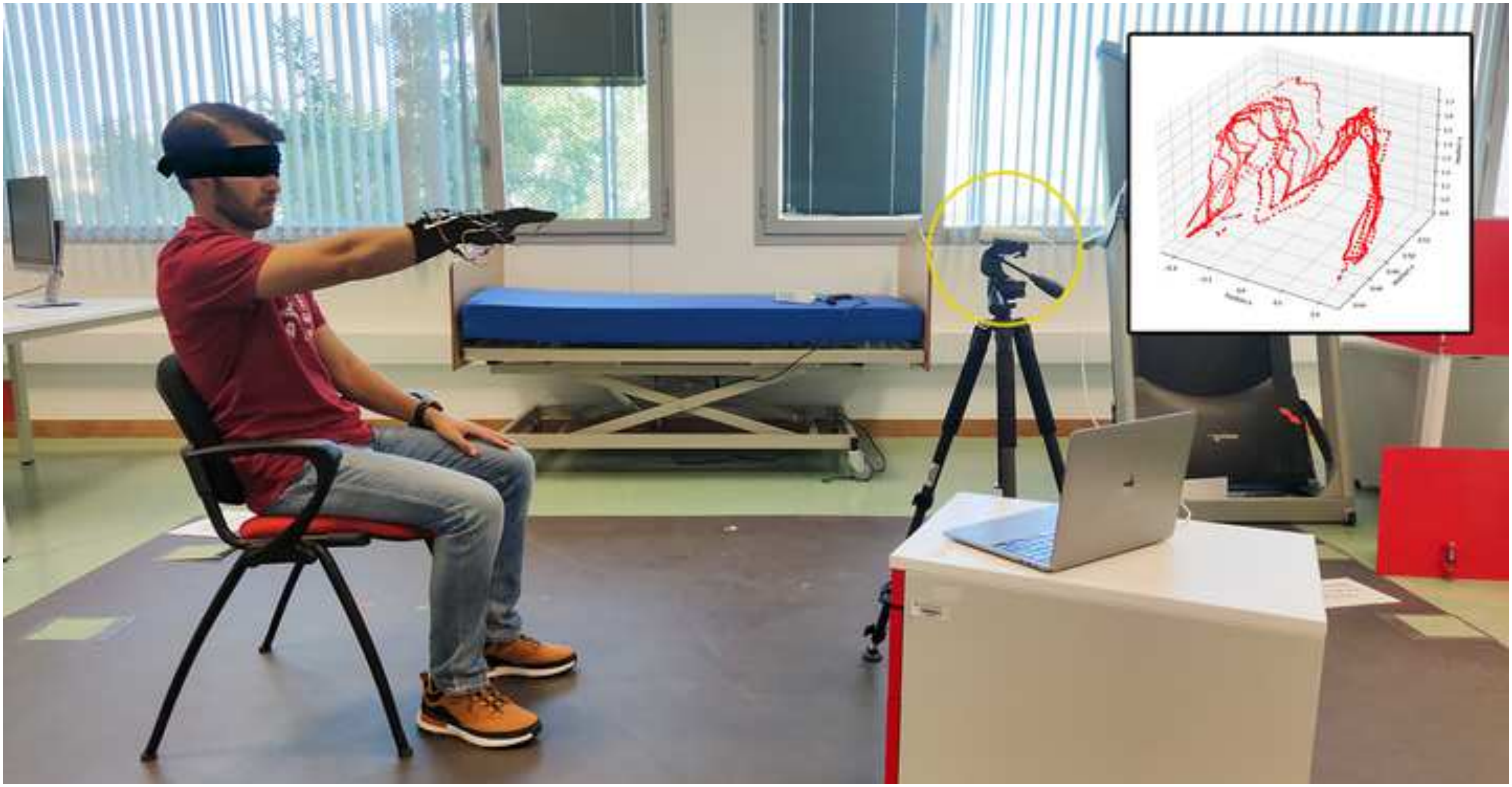

Figure 6

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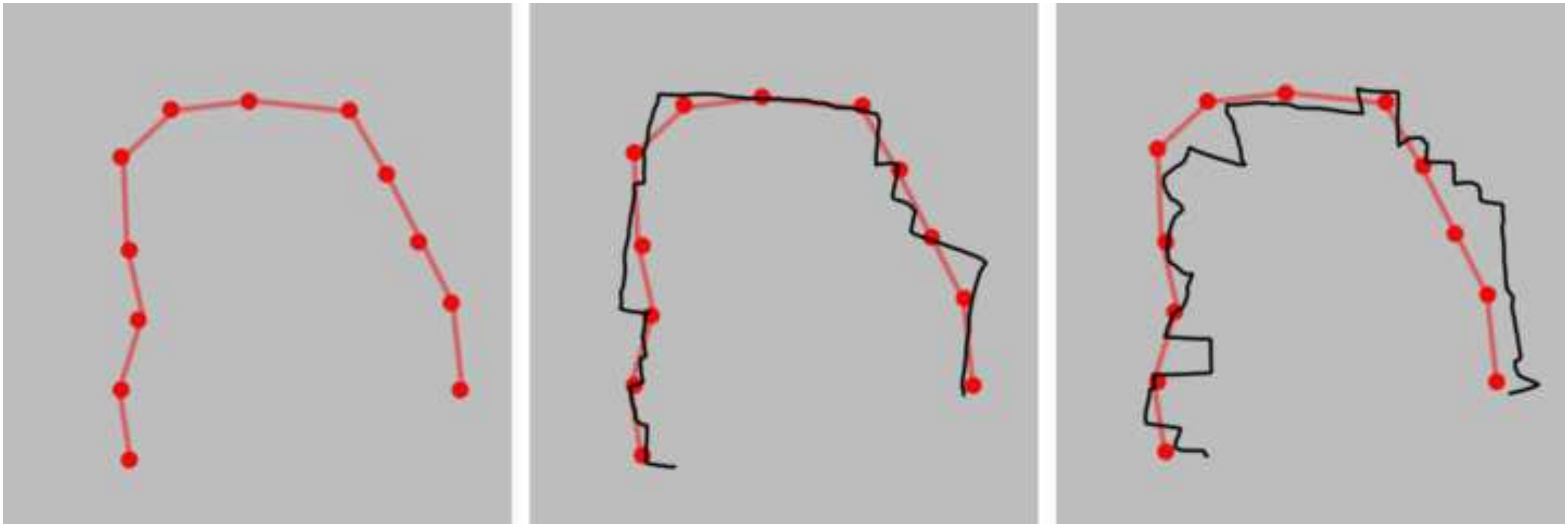

Figure 7

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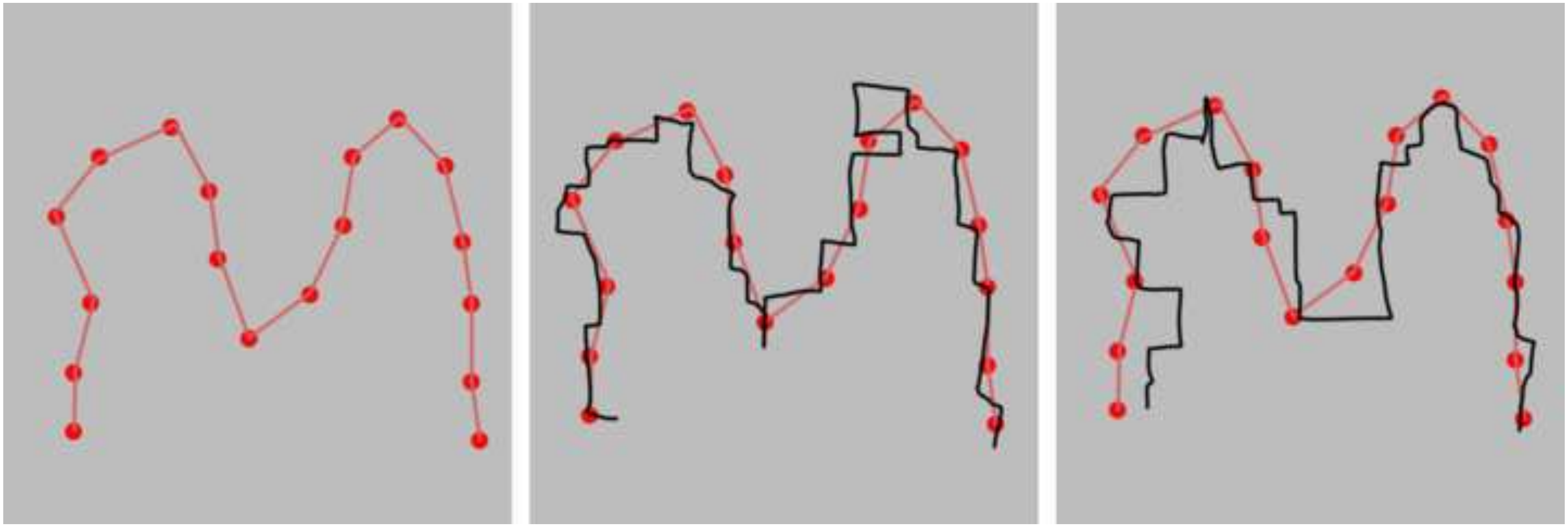

Figure 8

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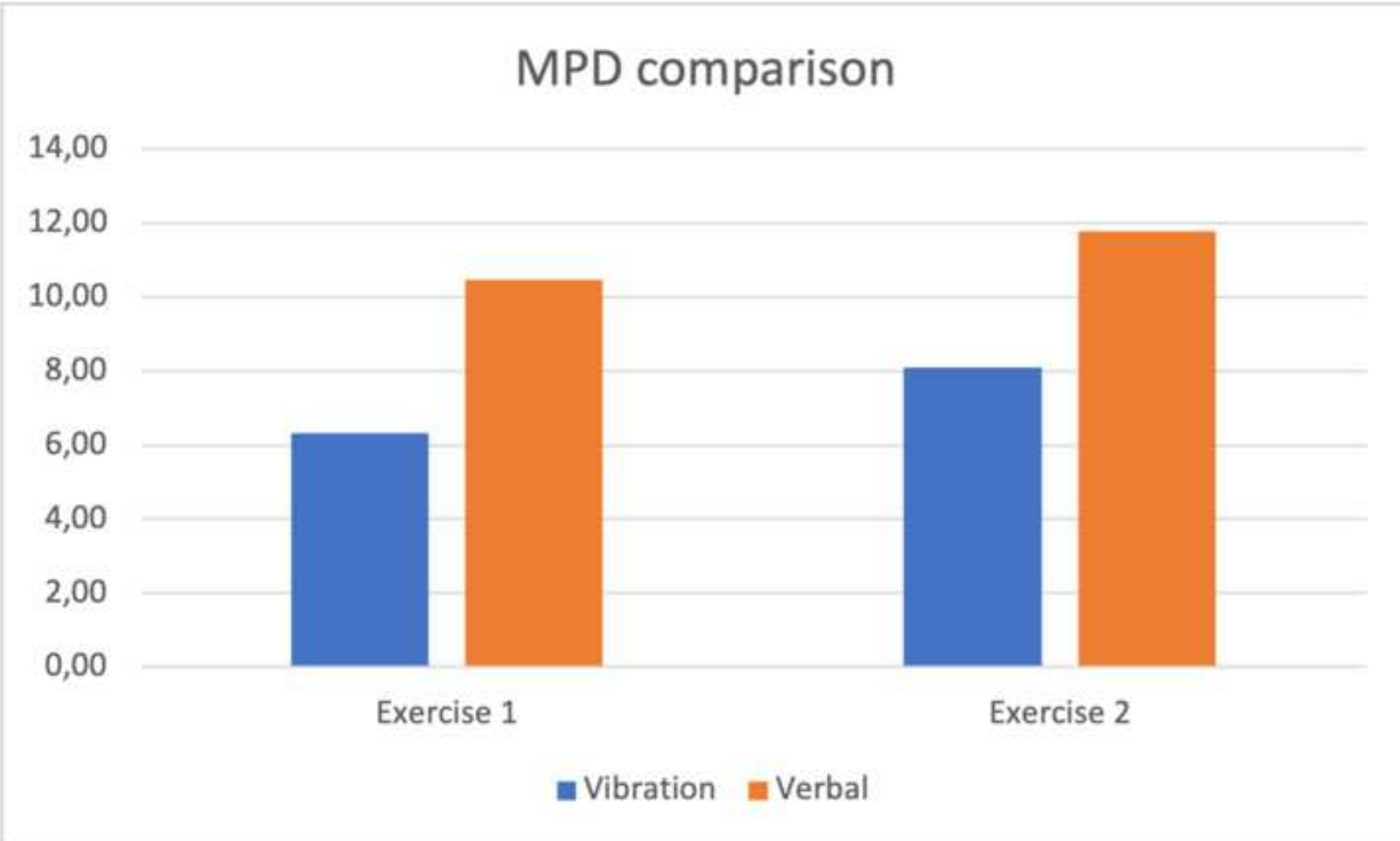

Figure 9

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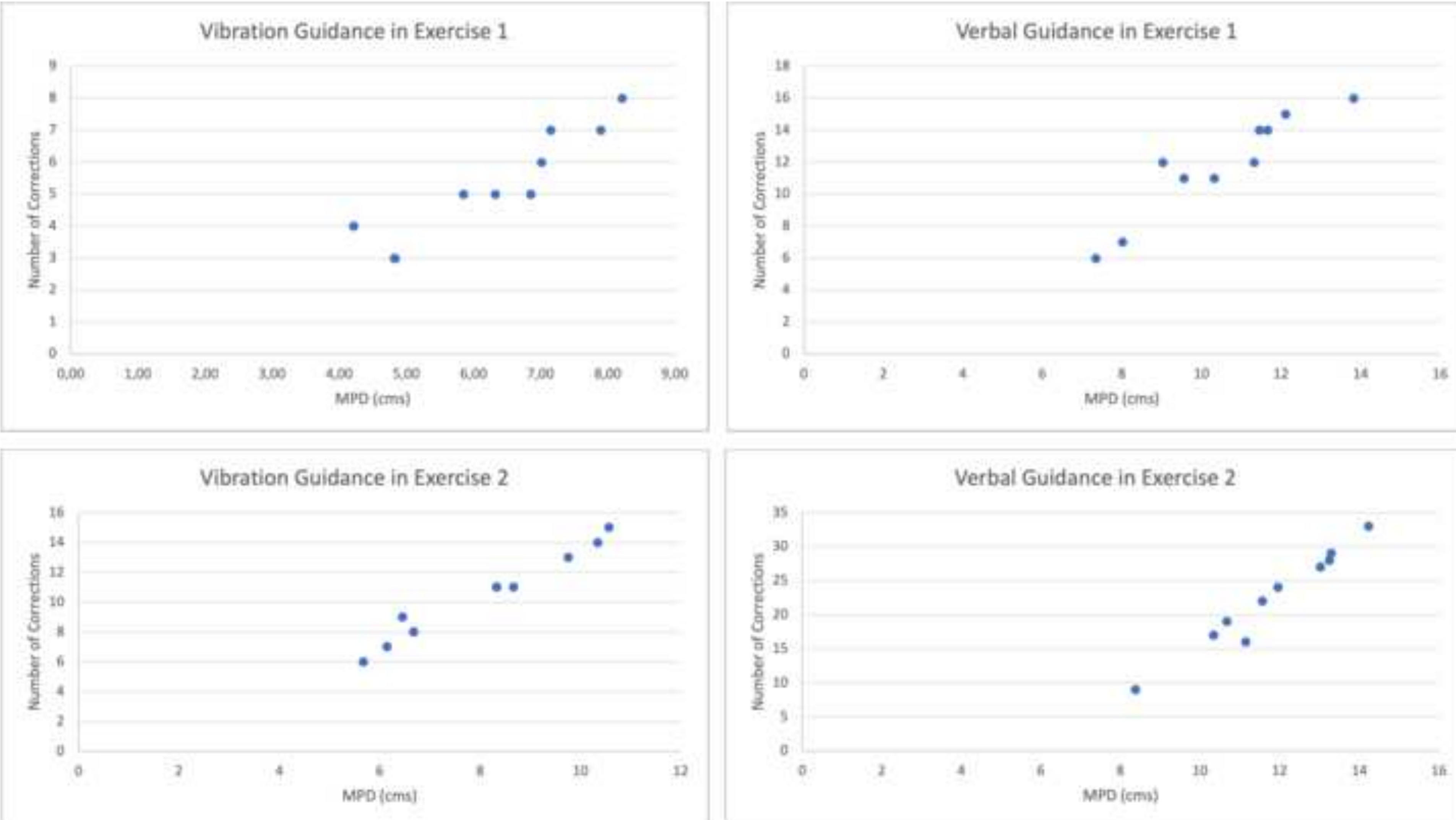

Figure 10

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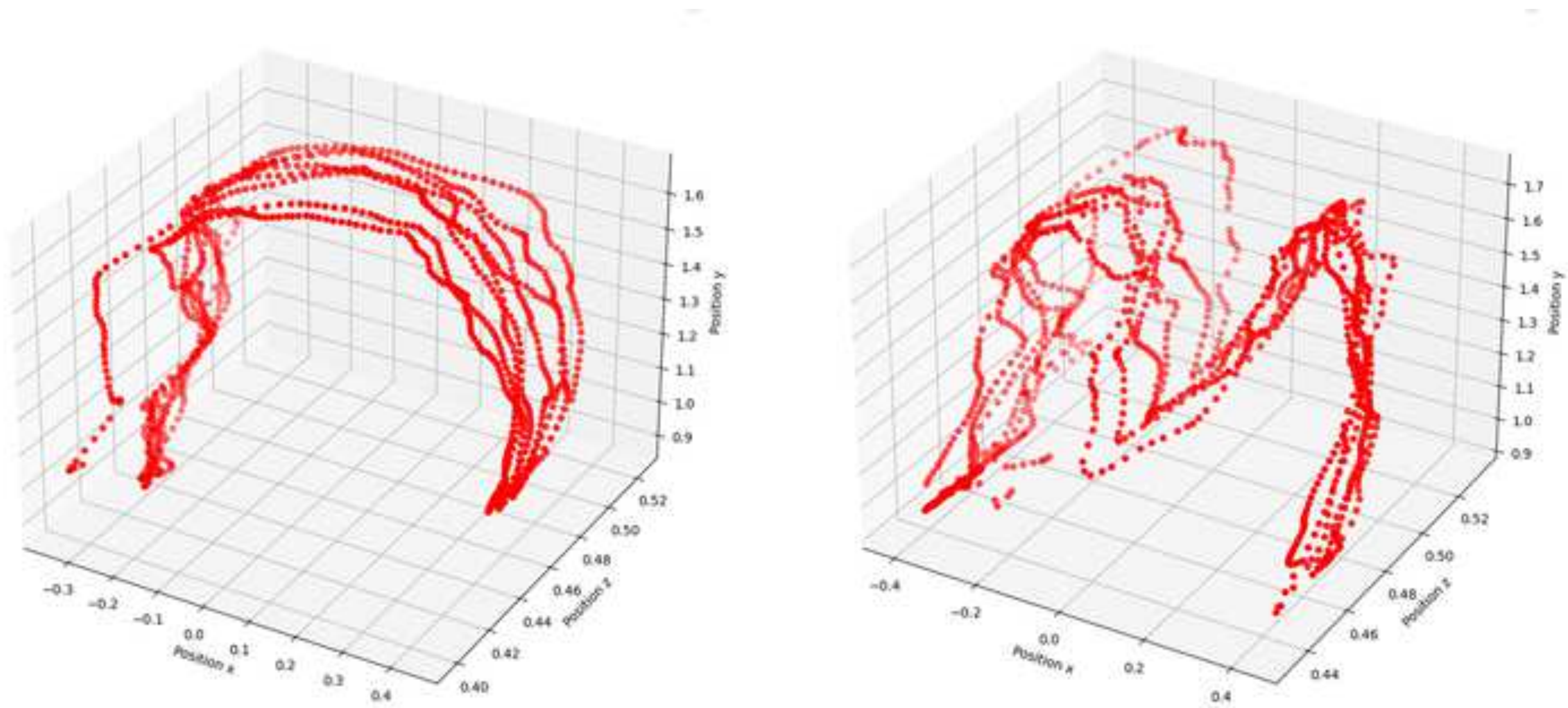

Figure 11

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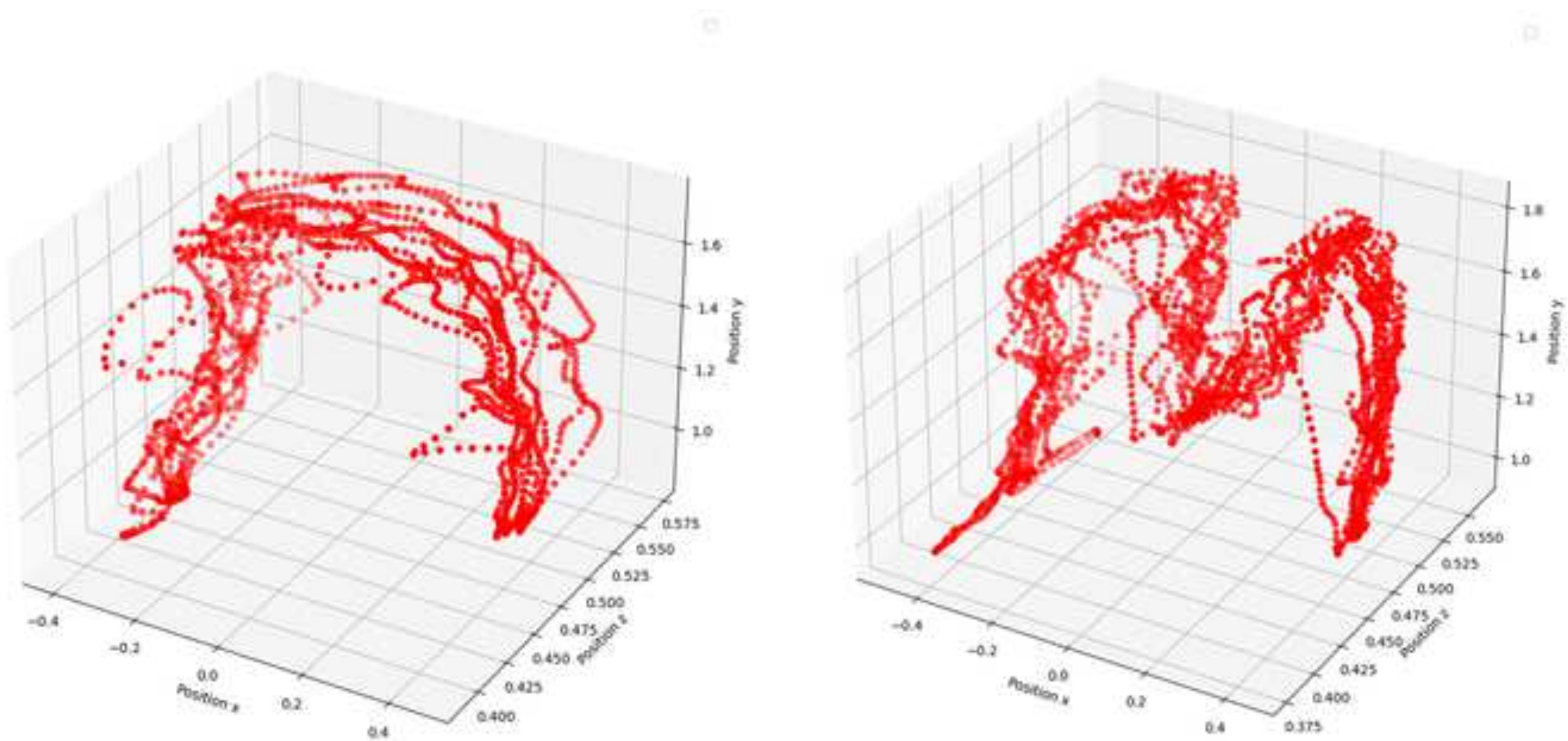

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