Hosseini *et al. BioMedical Engineering OnLine* (2025) 24:116
https://doi.org/10.1186/s12938-025-01411-7

BioMedical Engineering OnLine

RESEARCH

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Combining nonlinear mechanical stimulation via a chaotic mathematical model and game-based exercise for upper extremity rehabilitation in children with spastic hemiparetic cerebral palsy: a pilot study

Parisa Hosseini[1], Mohammad Ebrahim Hashemi[1], Zeinab Ziaee Fard[1], Donya Zafar Jafarzadeh Noghani[1], Zahra Ghanbari[2], Narges Hashemi[2], Mehran Beiraghi Toosi[2], Javad Akhondian[2], Ali Ghanaei Chamanabad[3], Tahereh Sadeghi[4] and Hamid Reza Kobravi[1*]

*Correspondence: hr.kobravi@iau.ac.ir

[1] Research Centre of Biomedical Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran
[2] Department of Pediatrics, School of Medicine, Mashhad University of Medical Sciences, Mashhad, Iran
[3] Associate Professor of Education and Psychology Faculty, and Member of Cognitive sciences Core, Ferdowsi university of Mashhad, Mashhad, Iran
[4] Nursing and Midwifery Care Research Center, Akbar Hospital, Mashhad University of Medical Science, Mashhad, Iran

Abstract

Background: Designing an upper extremity neurorehabilitation protocol for children with unilateral cerebral palsy (UCP) is a significant challenge. In this study, a combined rehabilitation protocol is proposed for restoring upper extremity function in children with unilateral cerebral palsy.

Methods: The proposed protocol combines mechanical stimulation of cutaneous mechanoreceptors on the back of the affected hand with computer game-based training. Drawing on insights into neural self-organization, a chaotic model was identified and utilized to generate the stimulation pattern. The efficacy of the proposed approach was evaluated in four patients.

Results: The results were analyzed across various clinical and signal-processing aspects. The clinical findings are promising, demonstrating intriguing improvement in wrist flexion and extension motion following the interventions. Additionally, nonlinear analyses of EMG dynamics and muscle activation timings suggest that the creation of a new motor program post-intervention is plausible.

Conclusion: Clinical analyses and nonlinear analysis of EMG dynamics supported the emergence of neuroplasticity following the designed rehabilitation protocol.

Background

Neurorehabilitation for children with UCP remains a challenging research problem. UCP commonly impairs the use of one hand and disrupts bimanual coordination, necessitating the development of targeted rehabilitation protocols. However, atypical brain reorganization following early brain damage complicates the selection of effective rehabilitation strategies [1]. Moreover, the location and size of the brain lesion can influence the effectiveness of therapy [2]. In light of these challenges, designing and adopting rehabilitation methods that expedite neuroplasticity in patients seems a justifiable strategy. As a result, the concept of neuroplasticity-informed rehabilitation has been introduced by some researchers [3–5]. The primary aim of these studies is to determine how and when brain networks respond to therapy [6]. In other words, designing interventional protocols that facilitate brain network responses in children with UCP remains a significant challenge. Brain network responses and brain reorganization can be viewed as two sides of the same coin. Therefore, interventions that promote brain rewiring are often preferred. Neuromodulation is one promising candidate. Neuromodulation interventions are typically employed to enhance neural plasticity [7]. Neurostimulation is a well-established form of neuromodulation. It is believed that plasticity can be induced through a process known as stimulation-driven plasticity [7]. This concept is grounded in Hebbian principles [8]. Brain stimulation, threshold electrical stimulation (TES), neuromuscular electrical stimulation (NMES), and spinal neuromodulation are neurostimulation-based methods that have been applied for motor–sensory recovery in children with CP [9–12]. The effectiveness of transcranial magnetic stimulation (TMS) as an adjunct to constraint-induced movement therapy (CIMT) in improving bimanual coordination in children with UCP has been investigated and reported [6]. It has also been suggested that concurrent peripheral sensory stimulation and TMS of the motor cortex may be suitable for children with UCP [6]. Some researchers argue that among noninvasive brain stimulation (NIBS) techniques, transcranial direct current stimulation (tDCS) is more convenient for children with CP [13]. It has also been reported that tDCS can be useful in improving clinical upper limb motor scores and motor skills [9, 14–17]. Some findings have demonstrated the beneficial effects of joint treadmill training and anodal tDCS over the contralateral primary motor cortex on dominant side function [10]. Using lower limb exoskeletons can improve motor function [18]. Nevertheless, evidence suggests that combining robotic therapy with tDCS may be feasible for upper extremity rehabilitation in children with CP [19]. Improvement in sensorimotor function in children with CP has also been reported by combining noninvasive spinal cord neuromodulation with activity-based neurorehabilitation therapy [20]. Some evidence suggests that threshold electrical stimulation (TES) and neuromuscular electrical stimulation (NMES) can improve motor function in children with CP by enhancing muscle strength and blood flow [21–23]. Recent evidence highlights the positive effects of noninvasive transcutaneous auricular vagal nerve stimulation (taVNS) combined with CIMT on motor outcomes in infants with hemiplegia [24].

The authors believe that delivering a stimulation signal must pave the way for eliciting neuroplasticity, and that the stimulation pattern is a crucial factor. Despite the promising results reported in the above studies, no clear guidelines have been provided for designing an effective (optimal) stimulation pattern. However, some researchers have approached this issue from a different perspective. According to a significant theory, a lack of fractal complexity in environmental stimuli can lead to abnormal brain development [25]. Thus, it has been suggested that using fractal stimuli in sensory interventions may enhance neuroplasticity [25]. Since neurological disorders involve a loss of complexity in neural signals and structures, restoring neural complexity in a self-organizing system is a prerequisite for reorganization [25]. In other words, this could prepare the brain to modify its neural synchronization patterns. However, sensory stimuli with a nonlinear temporal structure are like planting seeds in fertile soil. Without actively engaging the brain in motion-related tasks, neurostimulation alone is unlikely to trigger neuroplasticity. In this study, and in line with the proposed concept, a novel method has been developed to design a fractal stimulus. In this research, mechanical stimulation was used instead of electrical stimulation. Mechanical stimulation of cutaneous mechanoreceptors is not only non-painful, but also easier to implement in terms of hardware. Finally, the effectiveness of fractal mechanical stimulation combined with game-based exercise in improving bimanual coordination in children with UCP was evaluated across various aspects.

Results

Analyzing the muscle activation pattern

Figure 1 illustrates a sample wrist muscle activation pattern extracted during an intervention. Figure 2 demonstrates the changes in activation timing of the wrist extensor/flexor muscles post-intervention. Notably, the percentage of muscle activation time decreased after the intervention sessions. The reduction in activation time of the FCR muscle (as the spastic muscle) may indicate a decreased involvement of the affected muscle. This reduction likely reflects changes in the muscle co-activation pattern, as the period during which both muscles were simultaneously active also decreased. These observations can be considered preliminary findings.

RQA-related results

Figures 3 and 4 depict the changes in RQA-related metrics following the intervention sessions. Due to the patients suffering from spasticity in their wrist flexor muscles, the RQA was conducted solely for the flexor carpi radialis EMG signals. Figure 3 illustrates the variations in RR, and Fig. 4 depicts the changes in entropy. Interestingly, RR and ENTR increased on average. At first glance, these results might appear contradictory, as an increase in entropy seems to conflict with the observed increase in RR. However,

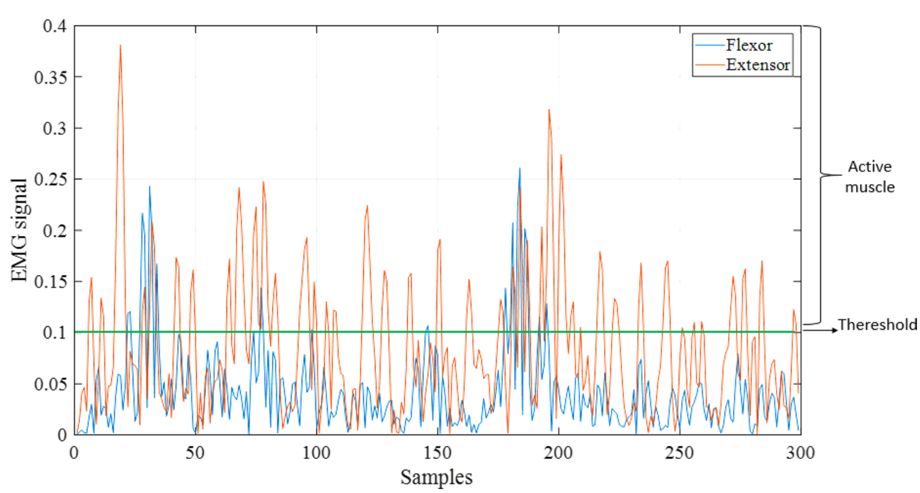

Fig. 1 A sample wrist extensor/flexor muscle activation pattern extracted during an intervention

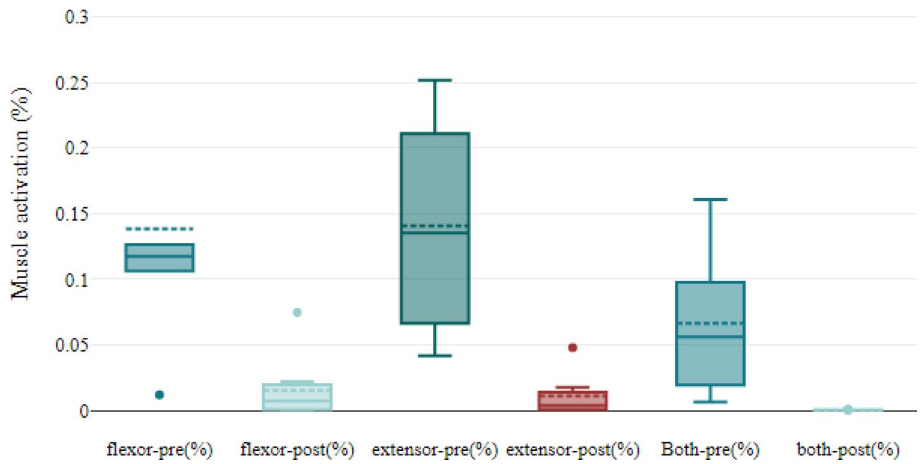

Fig. 2 Percentage of time the wrist extensor/flexor muscles are activated, computed before and after the intervention

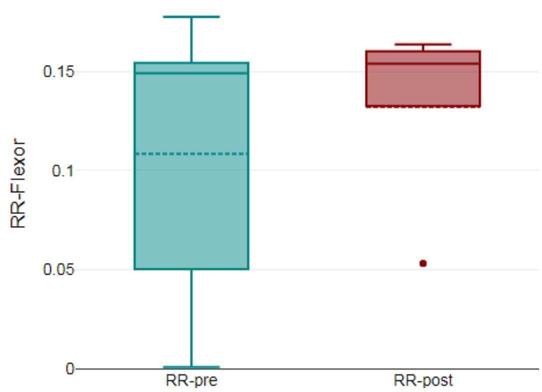

Fig. 3 The values of RR related to EMG signals of the wrist extensor muscle (upper chart) and wrist flexor muscle (lower chart), computed pre- and post- interventions

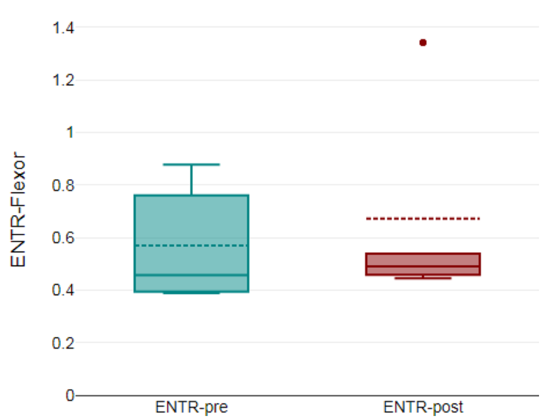

Fig. 4 The values of ENTR related to EMG signals of the wrist extensor muscle (upper chart) and wrist flexor muscle (lower chart), computed pre- and post- interventions

these findings can be consistent if one considers that a decrease in the probability of finding an l-length line within a recurrence plot does not necessarily contradict a more organized plot structure. This interpretation can be justified from a geometrical perspective.

Analysis based on FMA-UE

The differences in motor-related scores from the FMA-UE test were analyzed before and after the intervention. The mean score before the intervention was 48.25 ± 2.87, which increased to 56 ± 2.3 post-intervention. The differences in motor-related scores from the FMA-UE test were analyzed before and after the intervention. The mean score before the intervention was 48.25 ± 2.87, which increased to 56 ± 2.3 post-intervention. The principal component of the Fugl-Meyer Assessment for the Upper Extremity (FMA-UE) focuses on motor function. This section consists of four subsections dedicated to evaluating the upper extremity, wrist, hand, and coordination/speed. Within these subsections, there are 15 items that assess wrist dorsiflexion and volar flexion, various types of hand grasping, dysmetria, tremor, and hand motion time. Thus, an increase in the score related to motor function indicates an improvement in the diverse motor abilities of the upper extremity. Given that the minimum detectable change in the FMA-UE score is 1, an average increase of more than 7 points is significant. In other words, an intriguing improvement in upper extremity motor function, particularly in wrist joint movement, was observed. Motor function improvements were assessed by summing the scores of upper extremity assessment, wrist, hand, coordination, and speed. The results indicated intriguing improvement in wrist stability during dorsiflexion and repeated dorsiflexion/volar flexion exercises, while no improvement was noted in wrist circumduction. Overall, the proposed intervention has shown positive effects on motor abilities.

Discussion

Using computer games for upper extremity rehabilitation in children with hemiparetic cerebral palsy is a promising approach. However, designing an effective protocol remains a significant challenge. Using brain stimulation and spinal neuromodulation in conjunction with activities for upper extremity rehabilitation in children with cerebral palsy has shown promising results [19, 20]. However, the stimulation strategies mentioned are not able to specifically modulate sensory feedback; instead, they affect a broad area of the neural pathways. As a result, there is no clear understanding of how the information flow is modulated. Additionally, none of the discussed studies have addressed the design of a nonlinear stimulation pattern. Evidence [9–12] supports the beneficial role of incorporating external stimulation (electrical or mechanical). Although external neural stimulation appears to be a promising approach for accelerating neural recovery [9–12], designing an appropriate stimulation pattern remains an open research question. The primary question is: what constitutes an effective stimulation pattern? We believe that the stimulation signals must be designed to facilitate the emergence of neuroplasticity. We further propose that stimulating the sensory system may be particularly effective. Sensory input can serve as a gateway for modulating sensory information and influencing the synchronization patterns of neural networks involved in motor control. Disrupting existing neural couplings while performing goal-directed motor tasks may help realign the neural system towards new synchronization patterns, potentially leading to the formation of synaptic plasticity. However, we also believe that in a disordered neural system, nonlinearity and complexity are diminished. According to a proposed hypothesis, increasing fractal complexity in neural processes may help elicit neuroplasticity [25]. In the present study, this hypothesis served as the foundational concept. A novel method was introduced to design a chaotic mechanical stimulation pattern for delivering to skin mechanoreceptors on the back of the hand. The effectiveness of combining fractal stimulation with computer game training on upper extremity dynamics was evaluated in four children with UCP. The results are both intriguing and revealing. Clinical evaluations confirmed improvements in wrist motion, particularly in wrist dorsiflexion and volar flexion movements. Additionally, analysis of EMG dynamics revealed that post-intervention, RR values for wrist flexor muscle and ENTR values increased on average. These findings suggest that the EMG-related recurrence plots became more organized yet less predictable. A more organized recurrence plot could indicate improved organization of motor commands, potentially reflecting the development of new motor programs. However, reduced predictability suggests increased complexity, which aligns with the goal of designing a fractal stimulation pattern. Increased complexity in EMG signals may indicate the emergence of self-organizing behavior within the neural system. These observations suggest that activation of the wrist flexor muscle became more controllable through neural commands. Given that the wrist flexor muscle was spastic, these variations may indicate an increased role of the flexor muscle in wrist control. This finding aligns with the observed increase in motor-related scores from the FMA-UE test, as wrist control improved significantly following the interventions. Furthermore, the percentage of time the wrist extensor/flexor muscles were active decreased after the intervention sessions. Considering the previous findings, the reduction in activation time may be attributed to optimization of the muscle co-activation pattern. Improved wrist motion quality, achieved by altering the role of the spastic muscle, likely involves recruiting muscles with lower energy expenditure. This may indicate the formation of a new muscle synergy pattern. This is justifiable because increasing control of the spastic muscle corresponds with a reduced role of the antagonist muscle. It is important to note that wrist movement during the game was primarily flexion-based, as patients controlled the car's position using the joystick in the affected hand. This observation supports the previous analysis.

If the observed changes in EMG signals are a result of compensatory strategies, then the nonlinear features related to EMG would vary among different subjects. In other words, the changes exhibited by different patients do not follow a uniform pattern due to the inevitable anatomical and physiological differences among them. Additionally, the improvement in the voluntary control of a spastic muscle cannot be solely attributed to compensatory strategies, as this suggests the activation of certain spinal inhibitory reflexes, such as the autogenic reflex. It can be considered a facet of neuroplasticity.

Conclusion

Designing a comprehensive rehabilitation protocol for children with UCP is a significant challenge. Computer game-based methods hold potential effectiveness, as they allow for the implementation of various interactive training protocols. However, integrating additional interventions that can accelerate the neuroplasticity process is a compelling approach. External stimulation of the sensory system offers a promising solution. Mechanical stimulation of cutaneous mechanoreceptors is noninvasive and painless, offering advantages over other stimulation methods. However, designing an optimal stimulation pattern remains a challenging and debated issue. In this study, a novel design method was introduced based on a chaotic model. Stimulation of cutaneous mechanoreceptors on the back of the spastic hand was combined with a computer game-based training protocol. The computer game and related hardware were specifically designed to promote motor learning through a bimanual motor task. Overall, clinical evaluations involving four children with UCP demonstrated promising efficacy. Additionally, nonlinear analysis of EMG dynamics supported the creation of new motor programs, indicating the emergence of neuroplasticity. Although the obtained results support the proposed hypothesis, additional clinical studies involving a larger number of patients are necessary before this rehabilitation method can be widely adopted by clinicians. Additionally, including control groups that receive different linear stimulation instead of nonlinear stimulation could more effectively demonstrate the advantages of using chaotic stimulation. It is a prerequisite for more rigorous statistical analysis. Furthermore, follow-up monitoring, neuroimaging, and EEG processing should be performed in the subsequent phases of this study.

Materials and methods

Patient selection

Four children with hemiparetic cerebral palsy, aged 6 to 12 years (2 girls and 2 boys), participated in this study. Two main inclusion criteria were the absence of any motor-cognitive disorder except cerebral palsy (CP) and having sufficient muscle strength to operate the joystick. Thus, children with severe impairment based on the Gross Motor Function Classification System (GMFCS) were not included. Additionally, the children included in this study needed to be educable enough to understand instructions on how to play the computer game. Thus, children who were difficult or impossible to communicate with and instruct, were not included in the study. In other words, the cognitive level was evaluated qualitatively, and the GMFCS was determined to be sufficient for participants to meet the threshold required to play the computer game. The primary focus was that participants needed to be able to learn how to play and manipulate the joystick as needed to engage with the game. Pre-test and post-test assessments were conducted using the Fugl-Meyer Assessment for upper extremities (FMA-UE) as a sensorimotor evaluation scale [26]. Each patient participated in ten therapy sessions, each lasting about 20 min, repeated three times a week.

Big picture of the proposed concept

Reliable evidence reveals the presence of fractal geometry and dynamics in a healthy human brain [25]. As a result, distortion of fractality is associated with neurological pathology. Therefore, restoring fractal dynamics may serve as a prelude to effective therapy. The first prerequisite for effective therapy is inducing neuroplasticity. It has been proposed that fractal stimuli may result in artificially generated fractal dynamics [25]. It would be ideal to restore a specific type of fractal dynamics. However, the neural system comprises millions of interconnected neural networks, making it extremely challenging—if not impossible—to monitor and identify the complexity patterns that emerge within a normal neural system. Moreover, the lack of information regarding many underlying neurophysiological processes complicates the issue further. Therefore, it is necessary to adopt an approach that simplifies the problem. Increasing the fractality of sensory information through external stimuli appears to be a more feasible and straightforward option than trying to restore a specific fractal dynamic.

We believe that stimulating cutaneous mechanoreceptors during motor learning is a promising approach. Mechanical stimulation of Pacini and Meissner corpuscles transmits sensory information to the cuneiform nucleus, which then projects towards the inferior olivary nucleus (IO) [27]. Cerebral learning is facilitated through long-term synaptic changes induced in Purkinje cells (PCs) [28]. IO neurons convey error signals, with error-related information encoded through synchronization patterns, reflecting coupling strength among IO neurons [28]. Thus, stimulating cutaneous mechanoreceptors can regulate the synchrony among IO neurons and, consequently, modulate neural signal complexity, significantly impacting synaptic plasticity and learning. However, we believe that restoring or creating a fractal environment is only a necessary condition for inducing neuroplasticity and motor learning. Establishing new motor programs without training exercises and engaging cortical involvement in planning and executing motor tasks is unlikely. Therefore, combining a specific motor-cognitive task with fractal-patterned mechanical stimulation forms the core of the proposed concept. In this study, the target was rehabilitating bimanual coordination in children with UCP. The fractal stimulus was delivered to hand mechanoreceptors, and exercise therapy was designed around a specific bimanual task. In fact, the nonlinear stimulation signals were delivered throughout the entire duration of the task. This approach could enhance the modulation of neural signal complexity, significantly impacting synaptic plasticity and learning while performing the cognitive-motor task. Figure 5 delineates the proposed underlying concept. The design methods adopted are elaborated in the following subsections.

a) Mechanical stimulation pattern

a-1) Timing pattern

We believe the stimulation frequency should fall within the high-gamma band since this frequency range is closely associated with motor planning and neuroplasticity, maximizing the stimulus's effect [29, 30]. Some mechanoreceptors, such as Meissner's corpuscles, are best stimulated at frequencies between 10 and 80Hz, while others, such as Pacinian corpuscles, require stimulation at frequencies between 80 and 450Hz [31]. Therefore, mechanical stimulation was targeted towards Pacinian corpuscles. Figure 6 demonstrates the timing pattern for changing the stimulation frequency. During each T-second cycle, higher frequency stimulations (250 Hz) are delivered during the "ton" interval, while lower frequency stimulations (70 Hz) are delivered during the "toff" interval.

a-2) Variability pattern

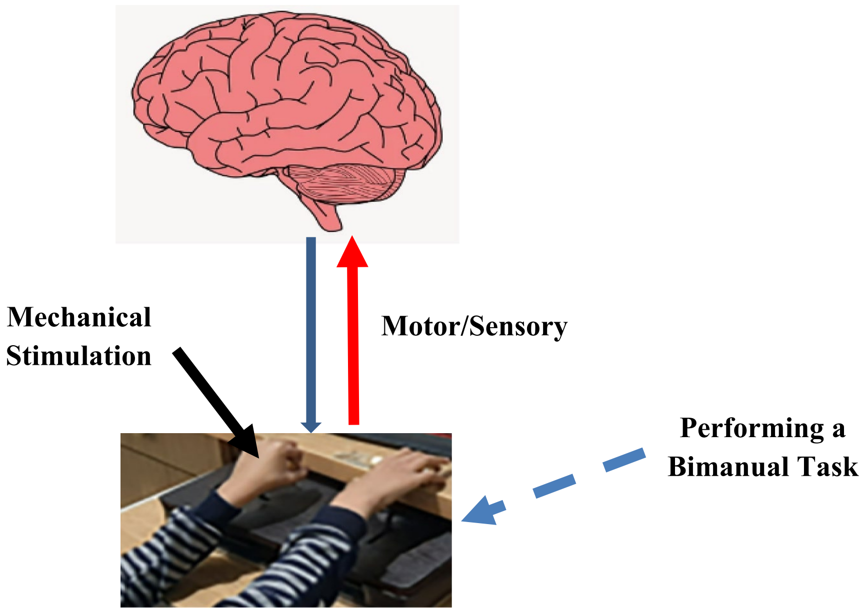

Fig. 5 A clear explanation of the proposed underlying concept that combines mechanical stimulation with a bimanual task

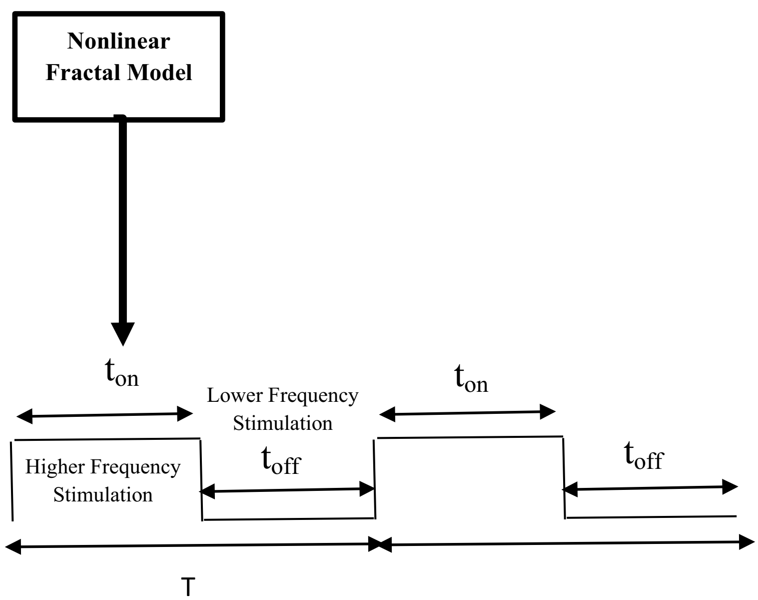

Fig. 6 Timing pattern for changing the stimulation frequency (T-second time cycle). During each T-second cycle, higher frequency stimulations are delivered during the "ton" interval, while lower frequency stimulations are delivered during the "toff" interval

As previously explained, the proposed neurorehabilitation approach is based on fractal mechanical stimulation. Three key parameters must be determined to design a fractal pattern: pattern structure, stimulation frequency, and variability. A fractal signal was needed, so one component of the stimulation signal had to be variable. Consequently, a chaotic model was identified and used as a nonlinear system to generate a fractal signal. A stimulation signal was designed with a variable parameter driven by fractal dynamics to activate Pacinian corpuscles (Fig. 6).

A logical approach to generating and describing a fractal signal involves using a chaotic model. Since the chaotic model needed to generate a one-dimensional time series to determine the stimulation pattern, a one-dimensional model was essential. Additionally, the model had to be discrete because it was designed to adjust the time duration of higher frequency stimulation within each 3-s cycle. The logistic map is one such example, and the presence of a self-similar structure within its bifurcation diagram has been demonstrated [32]. Furthermore, the mathematical implementation of the logistic map is straightforward, which can be an advantage for a nonlinear model. Thus, in this study, the logistic map model was used, as described in Eq. 1:

$$X_{n+1} = A.X_n.(1 - X_n). \tag{1}$$

Here, *Xn* represents the discrete state variable (ranging from 0 to 1) that determines the percentage of time higher frequency stimulation is delivered during the nth cycle. This series must exhibit fractal properties. The Hurst exponent (H) is a statistical measure that characterizes the properties of a time series [33]. In a self-similar time series, H is directly related to the fractal dimension (D) as follows [34]:

$$\mathrm{D} = 2 - \mathrm{H}. \tag{2}$$

In the context of the logistic model, the parameter A needs to be adjusted so that the fractal dimension, denoted as D, falls between 1 and 2. In this study, the A parameter of the logistic map was selected, and no system identification methods were applied. The parameter A was varied between 3.5 and 4 to achieve this, as the logistic map may exhibit chaotic behavior, resulting in increased fractal complexity. Within the range of $3.4 < A < 4$, both chaotic and ordered behaviors were observed. Specifically, ordered behaviors, known as U-sequences, emerged within the chaotic regime due to a high concentration of points near the critical point ($x = 0.5$), where the trajectory slope is 0 [32]. Notably, for $3.9 < A < 4$, the occurrence of U-sequences was found to be fewer compared to the range of $3.4 < A < 3.9$ (Fig. 7), suggesting a dominance of chaotic behavior. This chaotic behavior resembles self-organizing behaviors observed in biological systems, leading to more unpredictable patterns. Thus, for this study, the A parameter was varied from 3.9 to 4, and the corresponding fractal dimension for each A value was computed. The calculation of the fractal dimension using the Higuchi method for $A = 3.9$ resulted in a value of approximately 1.85, falling within the desired range of 1 to 2 for D. Therefore, $A = 3.9$ was selected as the model parameter, and the stimulation signal pattern was based on this value. The frequency shifting rate during each cycle was determined online using this pattern. Each cycle was set to a duration of 3 s to ensure that the mechanical stimulation was perceptible and allowed for sufficient time for signal processing and generation. Figure 8 illustrates a time segment of the generated pattern, determining the tone over each cycle.

b) Bimanual intervention

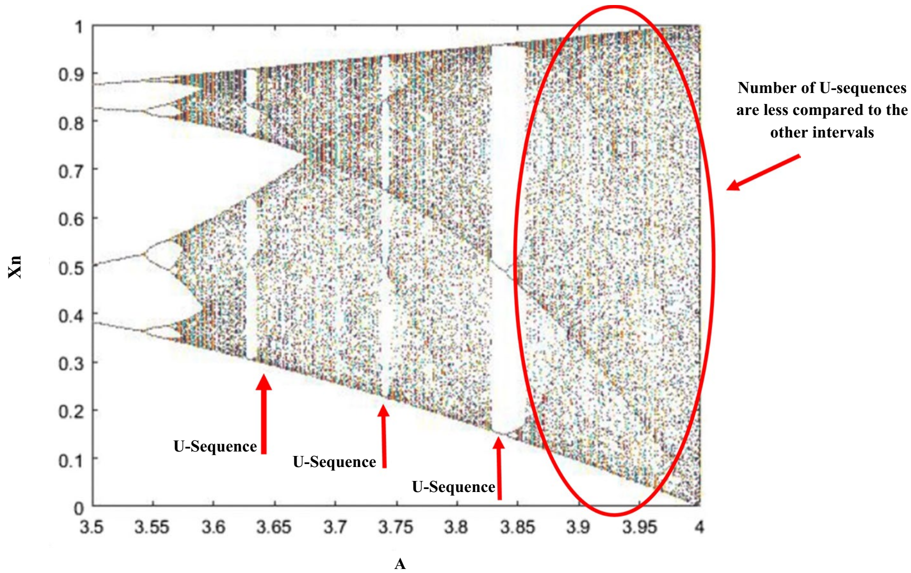

Fig. 7 Bifurcation diagram of the logistic map for 3.5 < A < 4

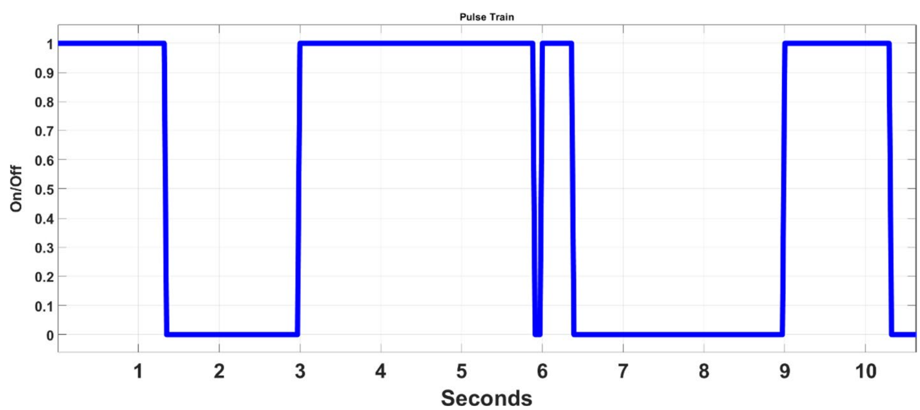

Fig. 8 The pattern of "ton" changes in cycles of 3 s over time. The "ton" is adjusted based on the output of the logistic model for each consecutive 3-s cycle

The exercise therapy was based on playing a specific computer game designed as a car racing scenario. The children used two joysticks for bimanual control, with the affected hand controlling horizontal movement and the healthy hand controlling speed vertically. A familiarization session was held for each child before starting the intervention. Figure 9 shows a child with left-sided hemiplegia playing the designed bimanual game.

Quantitative analysis based on electromyography

An intriguing aspect of post-rehabilitation evaluations is the change in EMG dynamics, which reflects the modification of motor commands and programs contained within the EMG signals. In this study, muscle coordination and the complexity of EMG dynamics were analyzed. The complexity analysis reveals the embedded nonlinear dynamics within a signal, where changes in the spatiotemporal regularity of

Fig. 9 A child with left-sided hemiplegia is playing a specially designed computer game using both hands while receiving mechanical stimulation to the backhand of the affected hand

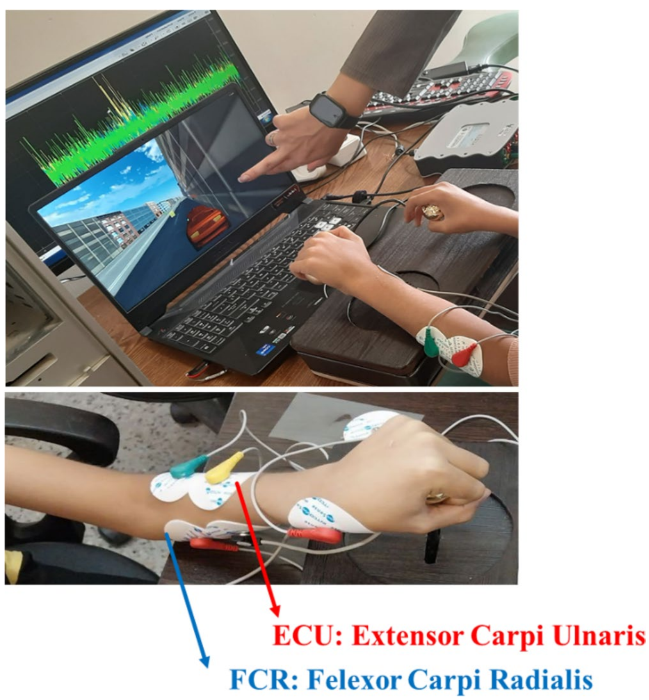

Fig. 10 Placement of the surface EMG sensors on FCR and ECU muscles

the signal indicate whether new motor programs have been restored in the brain. Given the game design and bimanual training task, the flexor carpi radialis (FCR) and extensor carpi ulnaris (ECU) muscles were selected to estimate muscle strength and synergy. The EMG signal from the affected arm (left arm) was recorded during the bimanual game. Figure 10 shows the placement of surface EMG sensors on the forearm. Electrode placement followed the SENIAM guidelines, and the skin was cleaned with alcohol for better contact before starting the protocol. EMG signals were measured using the g-tech system, sampled at 1200 Hz. Signals from the two EMG channels (FCR and ECU) were filtered and normalized before calculating muscle synergy. Each session involved EMG recording lasting approximately 2 min. With a sampling frequency of 1200 Hz, each trial contained around 1,440,00 samples.

The features related to muscle activation and EMG complexity of FCR and ECU in the initial and final rehabilitation sessions were compared. The specific features under analysis will be detailed in the following subsections.

- In terms of muscle activation

Changes in muscle co-activation patterns depend on the modification of motor commands, as muscle coordination reflects the neural commands at the muscle level. Quantitative features related to muscle activation time percentages were computed using a thresholding mechanism. EMG signals were filtered with a Butterworth bandpass filter (10 Hz-500 Hz), rectified, normalized, and filtered again with a lowpass Butterworth filter (cut-off frequency: 17 Hz). Features extracted included the duration of individual muscle activity and co-activation periods, expressed as relative percentages of total trial time.

- In terms of EMG complexity

Complexity is believed to arise from interactions among system elements, indicating non-isolated cooperation [35]. Analyzing changes in EMG signal complexity after intervention can provide insight into changes in muscle activation patterns due to the designed rehabilitation protocol. This study aimed to examine specific aspects of EMG signals that conventional linear methods cannot reveal. The objective was to explore how the irregularity patterns of EMG signals change as a result of the proposed neurorehabilitation protocol. This type of analysis could provide insights into the emergence or deterioration of self-organizing behaviors. In this study, recurrence quantification analysis (RQA) was used [36]. RQA quantifies recurrence behavior in dynamic systems by analyzing recurrence properties of phase space trajectories. Recurrence of trajectory $\overrightarrow{x_i}$ is quantified using Eq. 3:

$$R_{i,j} = \theta\left(\epsilon - \left\|\overrightarrow{x_i} - \overrightarrow{x_j}\right\|\right) \quad i,j = 1, \ldots, \text{N}, \tag{3}$$

where $\theta(.)$ is a Heaviside function, ϵ is threshold distance, and N is the number of measured points related to $\overrightarrow{x_i}$.

In this study, the false nearest neighbor algorithm was used to estimate the embedding dimension [37], which was determined to be m = 4 using a sample size of 5000 data points. The delay time was set to equal the sampling time, which is 1/1200 Hz, resulting in a delay of 0.8 ms. Since a bandpass filter with a bandwidth of 10 Hz to 500 Hz was applied, a sampling frequency greater than 1,000 Hz was enough to preserve the content of the recorded signals. Furthermore, the threshold parameter value (ϵ) was determined using a rule of thumb ($0.2\sqrt{m}$) [38].

Two RQA-related features have been studied as follows:

- Recurrence rate (RR)

RR measures the density of recurrence points in the recurrence plot. It is computed using Eq. (4) [36]:

$$RR = \frac{1}{N^2} \sum_{i,j=1}^{N} R_{i,j}, (\epsilon) \tag{4}$$

where N is the number of measured points and R describes recurrence of system trajectory in the phase space.

- Entropy (ENTR)

It measures the entropy of finding a diagonal line that its length is exactly l based on Shannon entropy formula using Eqs. (5) [36]:

$$ENTR = -\sum_{l=l_{min}}^{N} P(l)(P(l)), \tag{5}$$

where p is probability of finding a l-length diagonal line and Eq. (5) is Shannon entropy formula [36].

Clinical evaluations

The study did not include a control group. Because implementing a matched control group receiving other motor-cognitive rehabilitation protocols would have been challenging. Instead, the patients received no additional rehabilitation intervention during the study, and the same experimenters conducted the tests for all patients. Therefore, the study compared pre and post-intervention assessment results to attribute observed improvements to the designed method effectively. The study conducted pretest and post-test assessments using the Fugl-Meyer upper extremity test (FMA-UE) [26] to measure motor abilities. The Fugl-Meyer Assessment (FMA) scale is a clinical index used to evaluate sensorimotor abilities in individuals with motor impairments [26]. The scale items are scored based on direct observation of performance using a 3-point ordinal scale where 0 = cannot perform, 1 = performs partially, and 2 = performs fully [25]. The total score for evaluating upper limb performance ranges from 0 to 66, based on points obtained in the upper limb, wrist, hand, coordination, and speed categories. Sensation is scored from 0 to 12, and passive joint motion and pain are scored from 0 to 24 [26].

Acknowledgements
The authors express their gratitude to the esteemed children and their parents who took part in this study. We also appreciate the assistance of the Clinical Research Development Unit of Akbar Hospital in performing this research.

Author contributions
Study concept and design: H.K., P.H., M.H., N.H., M.B., J.A., and A.G.C.; Analysis and interpretation of data: H.K., P.H., Z.Z., D.Z., Z.G. and T.S.; Drafting of the manuscript: H.K., and M.H.; Critical revision of the manuscript for important intellectual content: H.K., and M.H.; Statistical analysis: P.H., and T.S.

Funding
This study was supported in part by a grant from the Cognitive Science and Technologies Council.

Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
This study was approved under the ethical approval code of IR.MUMS.MEDICAL.REC.1402.400. In addition, the study's objectives and methods were thoroughly explained to the participants and their parents, ensuring informed consent was obtained and confidentiality of personal information was assured.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 25 August 2024 Accepted: 11 June 2025
Published online: 09 October 2025

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