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Effect of Robot-Assisted Training on EEG-Derived Movement-Related Cortical Potentials for Post-Stroke Rehabilitation–A Case Series Study

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ABSTRACT This paper deploys movement-related cortical potential (MRCP), an electroencephalogram (EEG)-derived time-domain pattern, to assess the effect of robot-assisted motor training in seven post-stroke patients with hand impairment. Patients are divided into two groups of four subjects with supratentorial lesions and a group of three subjects with infratentorial lesions. Both groups participate in multiple-session motor training for their affected hand with an AMADEO rehabilitation robot. During pre- and post-training periods, three assessment procedures which include EEG signals derived from eight specific electrodes, hand-kinematic parameters, and clinical tests are performed. After four weeks of training, the negative peak of the MRCP signals shows a decrease across all electrodes and reaches significance in seven out of the eight electrodes for the first group according to paired t-test ($p < 0.05$). Whereas for the second group, the MRCP signal shows a decrease in its negative peak across all electrodes and reaches significance in two of the eight electrodes (paired t-test, $p < 0.05$) after eight weeks. Moreover, these MRCP changes show a positive association with improvements in kinematic parameters and clinical test results for both groups. Hence, this study shows that improvement of clinical outcomes in robot-assisted training is associated with a reduction in the amplitude of the MRCP signal. Furthermore, infratentorial stroke patients show a slower clinical improvement and require longer rehabilitation to produce significant changes in MRCP compared to subjects with supratentorial stroke.

INDEX TERMS EEG, motor training, movement-related cortical potentials, neuroplasticity, robot-assisted therapy, stroke rehabilitation.

I. INTRODUCTION

According to the recent annual report of the World Stroke Organization, approximately 14 million people had their first-time stroke each year and 80 million people live with the impact of stroke globally [1]. Among various effects of stroke, motor skills impairment is the predominant one. Specifically, the impairment of hand functions limits the independence of stroke survivors. The re-learning of lost motor functions is achieved with training strategies such as physiotherapy [2], [3], constraint-induced movement therapy [4], [5], mirror-box therapy [6], [7], virtual reality therapy [8], [9], and robot-assisted therapy [10], [11] which promote the mechanism of neuroplasticity. Neuroplasticity is a neurological adaption in the brain where new neural pathways are established, existing pathways are reinforced

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and adjacent surviving neuronal tissues assume the role of the damaged neuronal tissues [12], [13].

The effect of rehabilitation training on brain activities helps to better understand the mechanism of recovery after stroke which in turn can facilitate the development of advanced rehabilitation training strategies. There are numerous methods to capture brain activities during different motor training. Examples include electroencephalography (EEG) [14]–[25], magnetoencephalography (MEG) [26], functional magnetic resonance imaging (fMRI) [27], [28], functional infrared spectroscopy (fNIRS) [29], [30], transcranial magnetic stimulation (TMS) [31], [32] and transcranial direct-current stimulation (tDCS) [33]. Among these technologies, EEG is a low-cost, safe, and user-friendly method of recording brain activity. It has been a popular choice in various studies reported in the literature to determine motor training effects on brain activities [14]–[24].

One of the EEG-derived patterns associated with movement is called movement-related cortical potential (MRCP). MRCP is a time-domain, slow event-related potential that appears in the delta frequency band of EEG as a direct-current shift up to 2 seconds (s) before cue-based as well as self-initiated movements [34]. MRCP has three pre-movement components, which have been widely addressed in the literature that could indicate the effect of motor training [18]–[24]. The first pre-movement component is a slow decrease in the cortical potential that starts around 2s before movement onset (in this paper it is called Bereitschaftspotential 1 (BP1)). The second pre-movement component is a steeper decrease in cortical potential and starts at about 0.5s before movement onset (termed as Bereitschaftspotential 2 (BP2)). The third pre-movement component of the MRCP is the lowest negative potential near the movement onset (denoted as the negative peak (Npeak) throughout this article).

There is no consistent relationship reported in the literature between variations in the amplitude of MRCP components after participants underwent motor training or regained motor skills. In the study conducted by Taylor [18], the amplitude of MRCP increased with the improvement in response time after single-session training of finger motor tasks. Lang *et al.* [19] also observed an increase in the MRCP amplitude with improvement in task performance during a visual-motor activity. On the contrary, Niemann *et al.* [20] observed a significant decrease in the amplitude at some electrodes when healthy participants trained for a complex hand movement task. Some other studies also reported a decrease in the amplitude of the MRCP after the subjects achieved competency in motor tasks with practice [21]–[24]. Notably, all these studies demonstrate the effects of various motor training protocols in healthy participants on the MRCP signal. Also, these studies overlook the factor of stroke lesion location during motor training design and analysis of the results, though several authors reported that the post-stroke recovery depends upon the lesion location [35]–[40].

This paper reports a study conducted to investigate the variation of MRCP during motor training for post-stroke patients. It also aims to examine the effect of different lesion locations on the MRCP signal after completion of rehabilitation training in stroke patients. The outcomes of this work represent a stepping-stone in guiding therapists to adjust the rehabilitation training difficulty and to continually challenge stroke patients. As a result, this will produce higher degrees of brain neuroplasticity and enhanced consequent therapeutic outcomes in post-stroke patients.

In the approach deployed in this research, post-stroke patients underwent robot-assisted motor training of their affected hand with the help of an AMADEO rehabilitation robotic device [41]–[43]. An EEG acquisition system extracted MRCP signals during pre- and post-training protocols. The improvements in hand motor skills after the training were determined using clinical tests and hand-kinematic parameters measurement. The clinical tests included the Fugl–Meyer Assessment (FMA) and Motor Assessment Scale (MAS) for the upper extremity. The hand-kinematic parameters consisted of hand strength measured during flexion (force-flexion), hand strength measured during extension (force-extension), and hand range of movement (HROM). Also, variations in MRCP features were associated with improvements in the hand motor skills of the patients.

This innovative study provides a significant contribution to post-stroke rehabilitation research. The MRCP signal has been deployed previously to assess the effect of motor training but only for healthy subjects in non-clinical applications. For instance, Wright *et al.* [23] observed a reduction in the amplitude of MRCP features when participants learned to play guitar after five weeks of training. Jochumsen *et al.* [24] reported reduced MRCP amplitude when healthy participants completed six training sessions of simulated laparoscopic surgery training with their non-dominant hands. In this study, the MRCP signal is used to demonstrate the effect of designed robot-assisted training in post-stroke patients and identify the effect of stroke lesion location on the rehabilitation process. The results are validated by benchmarking against standard clinical methods.

The remainder of this paper is structured as follows. Section II provides details of equipment used in the experimental work and participants' information. The pre- and post-training protocols, as well as motor training protocols, are detailed in Section III. Section IV discusses the data processing and statistical analysis methods. The EEG data analysis and the results from the clinical tests and the hand-kinematic parameters for both groups A and B are provided in Section V. Section VI describes the extended study of group B and its results. The highlights of the main findings, implications, and limitations of the work done are given in Section VII. Finally, some conclusions are drawn, and the future work directions are discussed in Section VIII.

II. EXPERIMENTAL DESIGN

In this section, an introduction to the AMADEO rehabilitation device and EEG acquisition system used in the experimental work is provided. In addition, the details of the participant who took part in training sessions are discussed.

A. AMADEO HAND REHABILITATION DEVICE

Robot-assisted therapy is widely investigated and deployed in clinical practice for the rehabilitation of post-stroke patients [41], [44]. AMADEO (Tyromotion GmbH, Graz, Austria) is a state-of-the-art rehabilitation device designed for fine motor skill improvement in patients with stroke and spinal cord injury [42]. It is gaining significant interest in both research and clinical communities [41]. AMADEO is specially designed for distal upper-extremity motor recovery of patients [43]. It has five degrees of freedom that allow passive, assistive as well as active movement (with the help of 2D interactive games) of fingers and thumb. Many studies have used AMADEO for post-stroke rehabilitation [45]–[47]. For instance, Xianwei *et al.* [46], [47] used AMADEO for fine finger motor recovery of post-stroke patients. A novel algorithm incorporating assist-as-needed, integrated into AMADEO demonstrated a 35% increase in hand movement. The same research group studied the effect of 18 sessions of motor training with AMADEO on stroke patients and showed significant improvements in finger strength, range of hand movement, and coordination [48].

In this work, an AMADEO standard therapy program is used for motor training of patients' stroke-affected hands. Moreover, the force-flexion, force-extension, and HROM parameters were measured for all patients during pre- and post-training protocols using the AMADEO assessment tool.

B. EEG ACQUISITION SYSTEM

In this experiment, EEG signals are used to extract the MRCP signal for self-paced hand movements. The EEG signals were recorded using 32-channel Ag/AgCl Quick-Cap (Compumedics-Neuroscan) according to the 10–20 electrode positioning system. The Grael 4K EEG amplifier was configured for a sampling frequency of 2048Hz, bandwidth DC-2048 Hz, resolution 24-bit, and input range of 600mVpp. The FPz electrode was used as a ground electrode and a separate electrode was placed on the ipsilateral earlobe as a reference. The impedance of each electrode was set below 5kΩ. The EEG acquisition software used in this experiment was CURRY 8X (Compumedics-Neuroscan), which allows both offline and online data processing.

C. PARTICIPANTS

The following inclusion criteria were formulated for the recruitment of participants for the designed motor training:

(1) Range of age: 50-85

(2) Clinical stroke within 6 months to enrolment and MRI scan evidence of stroke consistent clinical presentation

(3) Stroke lesion location isolated to either supratentorial or infratentorial region

(4) Major impairment: hand motor (fine finger motor) deficits

(5) Impairment level: motor abilities suggested by MAS score (Section 7, hand movements, 1-5)

(6) Good cognition: suggested by widely adopted Rowland Universal Dementia Assessment Scale or Mini-Mental State Examination score of 26 or more out of 30 [49]

(7) Ability to understand verbal instructions in English

Based on the inclusion criteria, four post-stroke patients having supratentorial stroke lesions, and three patients with stroke in infratentorial regions were identified. All patients were right-hand dominant and had an ischemic stroke. The characteristics of all stroke patients are listed in Table 1. It is noted that all infratentorial stroke patients have a lesion location in their brain stem. Every patient also received standard care at a local hospital, in addition to our intervention training protocol using the AMADEO device. The participants gave their written informed consent before the experiment commencement.

The MAS-hand movement test scores in Table 1, acquired at the beginning of the motor training program, indicate that the patients in group A had better baseline finger movements while group B patients had limited finger movements consistent with the location of the lesion in their brain stem.

III. TRAINING INTERVENTION

This section explains the pre- and post-training protocols as well as motor training protocols that each participant performed for assessment and training purposes, respectively.

A. PRE- AND POST-TRAINING PROTOCOLS

Three measurements were recorded for each patient in both groups A and B in weeks 0 and 4.

1) MEASUREMENT 1

The EEG signal was acquired while the subjects were asked to perform self-paced simple hand grasping movements with their affected hand in 8 to 10 blocks of 10 trials each as shown in Fig. 1 (a). The time gap between any two trials was randomly varied between 8s to 10s. Patients focused their vision on a cross-mark to avoid random eye-movement artifacts. On each movement trial, a digital trigger was manually sent to the acquisition software (CURRY 8X, Compumedics-Neuroscan) which was used to divide the continuous EEG data into epochs of 10s duration during offline processing.

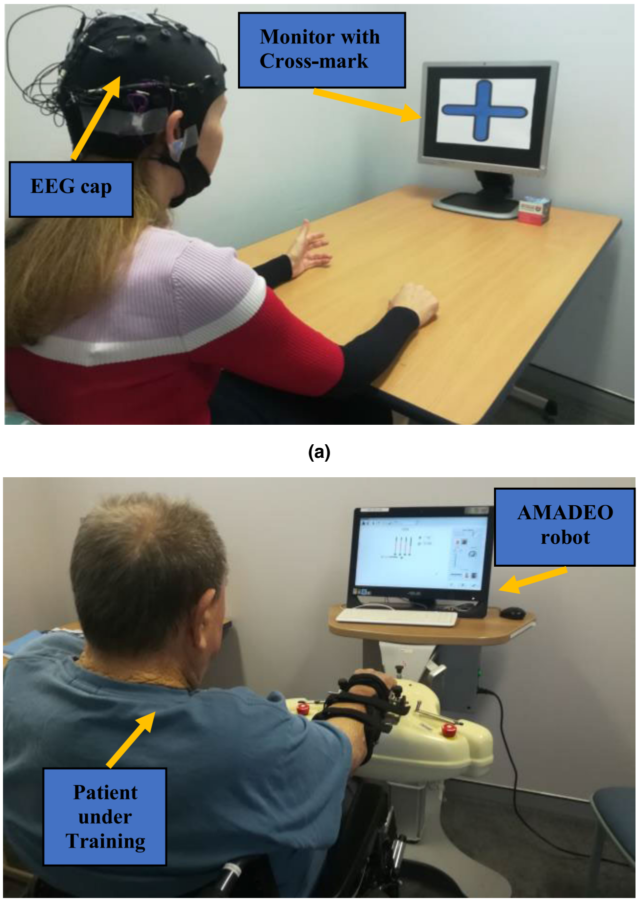
2) MEASUREMENT 2

The clinical tests namely the FMA test (wrist and hand sections only) [50] as well as the MAS test [51], for both hand movement and advanced hand movements, were performed to assess the current hand motor abilities of patients. These clinical tests were denoted as FMA-wrist, FMA-hand, MAS-hand movements, and MAS-advanced hand movements in this article.

TABLE 1. Basic characteristics of each stroke patient based on inclusion criteria.

Category	Stroke Patient (Gender)	Age (Years)	Stroke Lesion Location	Stroke Onset Duration (Months)	Affected Hand	MAS-Hand Movement Test
Group A	SP1* (Male)	82	Left motor cortex	3	Right	2
	SP2 (Male)	81	Left thalamic and internal capsule	2	Right	3
	SP3 (Male)	67	Left internal capsule	2	Right	2
	SP4 (Female)	51	Right basal ganglia	1.3	Left	4
Group B	SP5 (Female)	64	Left pons	4	Right	1
	SP6 (Male)	60	Left ponto-medullary junction	3	Right	1
	SP7 (Female)	63	Right pons	6	Left	1

* SP stands for Stroke Patient. It is an arbitrary name given to each participant.



(a)

(b)

FIGURE 1. (a) Patient performing self-paced hand grasping tasks during pre- and post-training protocols. (b) Patient performing training on AMADEO robot during motor training protocol.

3) MEASUREMENT 3

The force-flexion, force-extension, and HROM parameters for the affected hand were measured using the assessment tool available in the AMADEO rehabilitation device.

B. MOTOR TRAINING PROTOCOLS

AMADEO standard therapy programs were utilized for motor training of the affected hand for both A and B groups.

TABLE 2. Motor training program for groups A and B.

Category	Training Program
Group A	Step1: CPM training mode for 5 minutes. Step 2: CPMplus training mode for 5 minutes. Step 3: Assistive training mode for 10 minutes; and Step 4: Active training mode (2D interactive games) for 10 minutes.
Group B	Step 1: CPM training mode for 10 minutes. Step 2: CPMplus training mode for 10 minutes; and Step 3: Assistive training mode for 10 minutes.

AMADEO allows four basic training programs which include Continuous Passive Motion (CPM), CPMplus, Assistive therapy, and Active therapy programs. In CPM, the hand is trained in continuous passive motion. During CPMplus, the subject is encouraged to apply force during extension and flexion actions of the hand through a biofeedback display. While in assistive therapy, the hand movement is assisted by the AMADEO control algorithm, depending on individual fingers' functional limitations and abilities. Lastly, the active therapy utilizes 2D interactive games in which the patient performs target-oriented tasks actively in various simulated environments. Figure 1 (b) shows the patient receiving training on one of the AMADEO training programs. In the beginning, the HROM for each patient was set according to the AMADEO protocol to the maximum potential range depending on each patient's hand size. The duration of each training session was 30 minutes and patients received three training sessions weekly for up to four weeks (12 training sessions). The total training duration for each patient was 360 minutes in one month. However, patient SP7 completed 10 motor training sessions instead of 12 due to personal circumstances. The specific training programs for groups A and B are presented in Table 2.

Although the total duration of motor training for group A was designed to be the same as group B, active training mode was included only in group A training protocol because stroke patients in group B were unable to play the 2D games

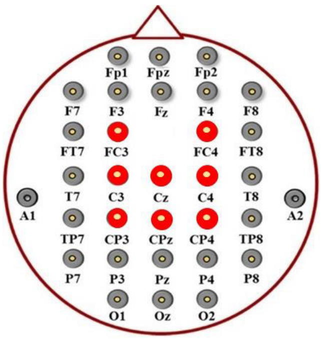


FIGURE 2. **Positions of selected electrodes for this experiment.**

with their initial finger movements. At first, it was decided to compare the results of four weeks of training for both groups. However, it was anticipated that the participants in group B might require a longer training period due to lesion location in their brain stem [52].

IV. DATA PROCESSING AND STATISTICAL ANALYSIS

Eight single EEG electrodes were used for the analysis (FC3, FC4, C3, C4, CP3, CP4, Cz, and CPz). In the literature, the C3, Cz, and C4 electrodes are commonly used to extract MRCP signals for hand motor tasks [18]–[24]. In addition, five other electrodes (FC3, FC4, CP3, CP4, and CPz) were explored in this experiment. The positions of all these selected electrodes in 32-channels Quick-Cap are shown in red color in Fig. 2. EEG signals from each selected electrode were first passed through a notch filter (49–51 Hz) to remove any power line noise. They were then passed through a low-pass filter with a 5Hz cut-off frequency and a high-pass filter with a 0.5Hz cut-off because MRCP signals lie in the delta band range of 0.5–5 Hz [53]. The filtered EEG data were then divided into epochs using event triggers. The duration of these epochs was set from -5s to 5s and where 0s was the onset of the movement. It is noted that MRCP has the lowest potential around the movement onset point [24], [34]. After epoch formation, the independent component analysis (ICA) algorithm was applied to remove eye-related artifacts from the data [54]. These 10s epochs were termed as long epochs. Short epochs were then formed starting from -3s to 1s.

Epoch data were averaged to obtain MRCP signals at all eight electrode sites. For those patients who performed the movement with their right hand, odd number electrodes (FC3, C3, and CP3) were contralateral channels and even number electrodes (FC4, C4, and CP4) were ipsilateral channels. The reverse was true for the patients who performed the left-hand movement. For group analysis, these electrodes were designated contralateral FC (CLFC), contralateral C (CLC), and contralateral CP (CLCP) to indicate the contralateral side for both right and left-hand movements. Similarly, to represent the ipsilateral side of both hand movements, the electrodes were designated ipsilateral FC (ILFC), ipsilateral C (ILC), and ipsilateral CP (ILCP). The electrodes Cz and CPz are central channels and therefore do not need to have their labels based on ipsilateral or contralateral positions. Hence, the electrodes used in the analysis were CLFC, CLC, CLCP, ILFC, ILC, ILCP, Cz, and CPz. The amplitude of the Npeak feature from averaged MRCP signals was extracted from the eight electrodes using a MATLAB toolbox called 'visualEEG' [55].

Along with EEG data analysis, clinical tests and hand-kinematic parameters measurements were also analyzed. The clinical tests (FMA-wrist, FMA-hand, MAS-hand movements, and MAS-advanced hand movements) were performed three times by each patient and the best scores were recorded according to the general rule of administration for these clinical tests. Whereas force-flexion, force-extension, and HROM parameters were also measured three times, but their average values were used during the analysis of the results. Statistical significance was calculated in all three measurements (MRCP signal features, clinical tests, as well as hand-kinematic parameters) using a two-tailed paired t-test. The significant level of the t-test is reported at the alpha value of $p < 0.05$.

V. RESULTS

In this section, the results obtained from the analysis of EEG data, clinical tests as well as hand-kinematic parameters for both groups A and B are discussed.

A. EEG DATA ANALYSIS RESULTS

In this section, results obtained from EEG data analysis for groups A and B are presented. For both groups, visible MRCP signals were obtained using the patients' data at all eight selected electrodes during pre- and post-training periods. The averaged pre- and post-training MRCP signals at all selected electrodes (ILFC, ILC, ILCP, CLFC, CLC, CLCP, Cz, and CPz) for group A and group B are shown in Fig. 3 and Fig. 4, respectively. The MRCP signals at all electrode sites are plotted for the time interval -1s to 1s for better visualization of the amplitude changes that occurred in MRCP Npeak after completing multi-session motor training. For group A, visual inspection of the MRCP plots indicates that the post-training values of Npeak of MRCP signals are prominently decreased at all selected electrodes compared to their corresponding pre-training values. Whereas MRCP plots for group B shows that the post-training Npeak values are considerably increased at ipsilateral electrodes (ILFC, ILC, and ILCP), slightly decreased at contralateral electrodes and one of the central electrodes (CLFC, CLC, CLCP, and CPz) but remains the same at Cz central electrode.

Fig. 5 (a) shows the column chart representation of the mean absolute pre- and post-data values of the Npeak features of the MRCP signal with error bars for each electrode position for group A. The error bars were calculated using the standard deviation (SD) values for all eight electrodes. The Npeak amplitude at all eight electrode positions decreased compared to pre-training values. The application of paired t-test on Npeak values of group A revealed that its post-training values were statistically significant at ILC

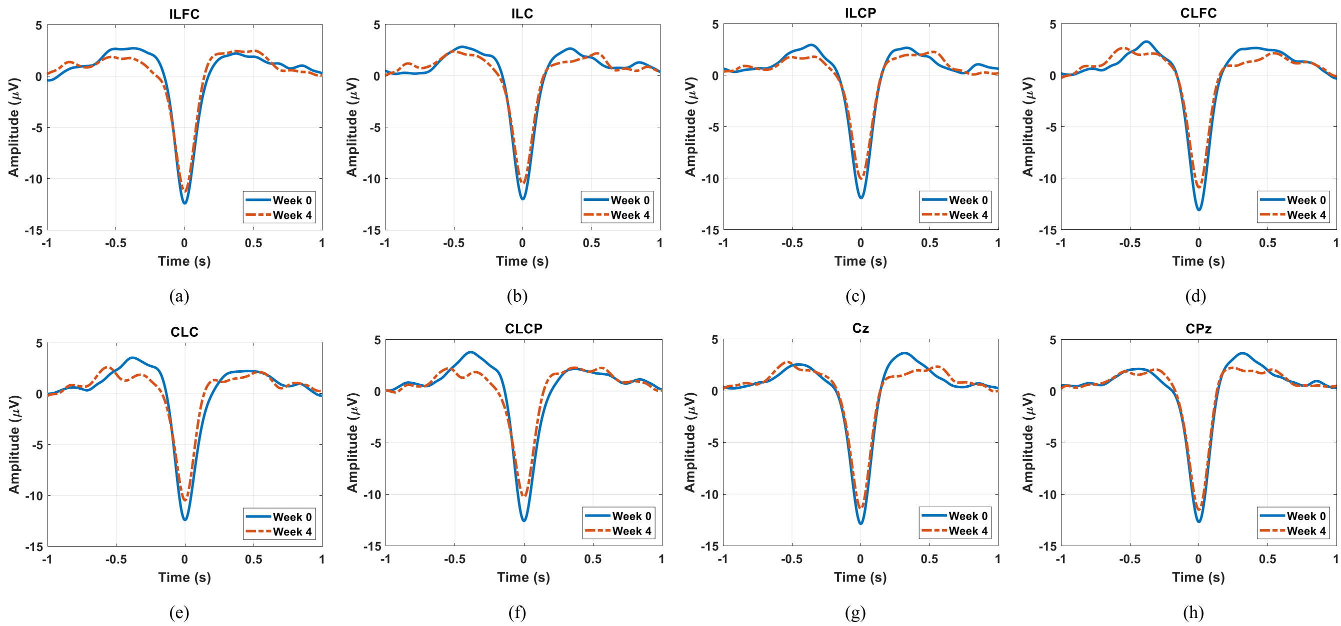


FIGURE 3. Average MRCP signals for group A at all channels after 12 motor training sessions, (a) ILFC, (b) ILC, (c) ILCP, (d) CLFC, (e) CLC, (f) CLCP, (g) Cz, (h) CPz. Legend Week 0 represents the pre-training period, and legend Week 4 shows the post-training period in all figures.

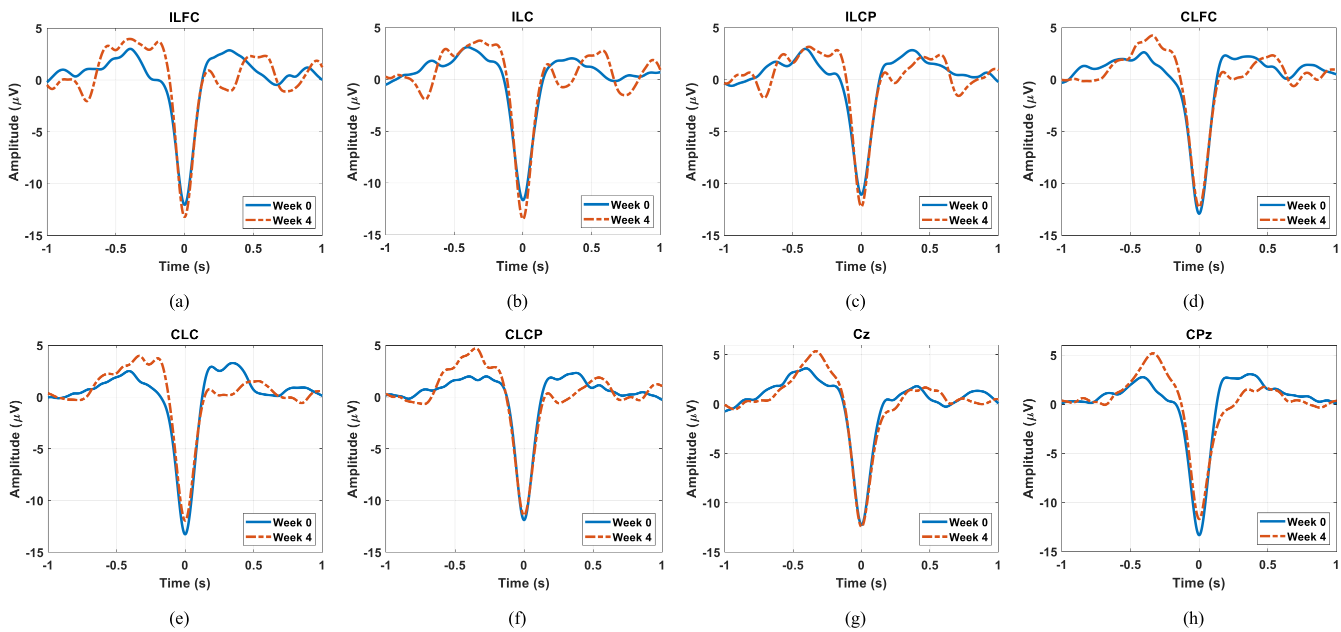


FIGURE 4. Average MRCP signals for group B at all channels after 12 motor training sessions, (a) ILFC, (b) ILC, (c) ILCP, (d) CLFC, (e) CLC, (f) CLCP, (g) Cz, (h) CPz. Legend Week 0 represents the pre-training period, and legend Week 4 shows the post-training period in all figures.

($p = 0.005$), ILCP ($p = 0.03$), CLFC ($p = 0.035$), CLC ($p = 0.027$), CLCP ($p = 0.019$), Cz ($p = 0.035$) as well as CPz ($p = 0.014$) compared to pre-training values as indicated by a '$*$' symbol in Fig. 5 (a). However, the decrease in post-training Npeak amplitude was not statistically significant at ILFC ($p = 0.118$). Hence, it was concluded that group A participants showed a statistically significant decrease in Npeak amplitude in seven of eight selected electrodes after completion of training.

For group B, Fig. 5 (b) shows the bar-chart representation for mean absolute pre- and post-training values for Npeak amplitude. An increase in all ipsilateral electrodes (ILFC, ILC, and ILCP) for post-training Npeak values was observed compared to their pre-training values. On the other hand, Npeak amplitudes at all contralateral and central electrodes (CLFC, CLC, CLCP, Cz, and CPz) either remained constant or decreased after the training. However, these changes were not statistically

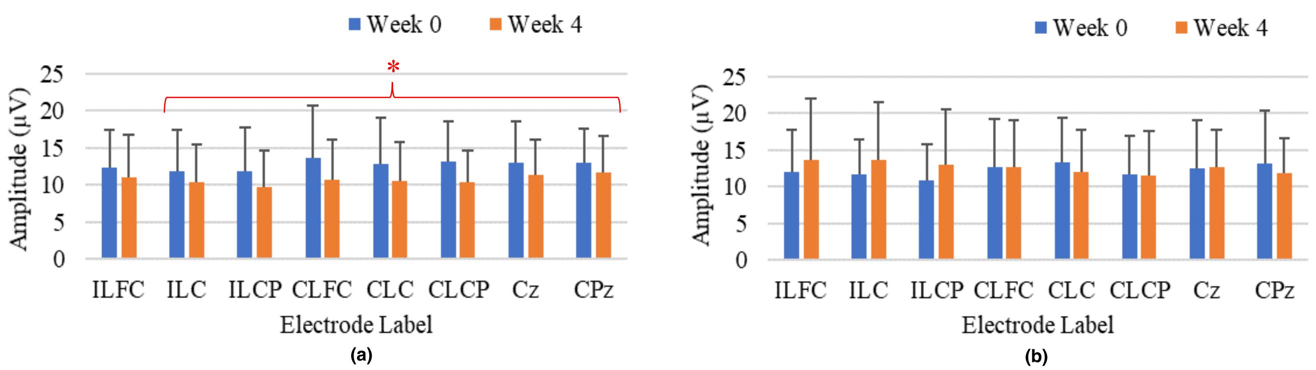


FIGURE 5. Mean absolute Npeak amplitude Week 0 and Week 4 periods (a) group A, (b) group B. The error bars represent SD values across subjects for each electrode. The symbol '∗' in Fig. 5 (a) indicates a significant decrease in Npeak amplitude at week 4 compared to that at week 0.

significant at any electrode's position according to the paired t-test ($p > 0.05$).

B. CLINICAL TEST RESULTS

FMA-wrist, FMA-hand, MAS-hand movements, and MAS-advanced hand movements' tests were executed at week 0 and week 4 of the designed robot-assisted training for each stroke patient in group A and group B. These clinical tests were used to determine the physical improvements in the hand motor abilities of the patients.

Table 3 shows the average values for four clinical tests of group A in the mean (±SD) form. The paired t-test was applied between pre- and post-training values on all four clinical tests. The significant change is indicated by bold values and a '∗' symbol on the values in Table 3. For group A, the paired t-test application showed statistically significant improvement in FMA-wrist ($p = 0.006$), FMA-hand ($p = 0.043$) as well as MAS-hand movements ($p = 0.035$) clinical tests after four weeks of training. However, the MAS-advanced hand movement clinical test ($p = 0.252$) did not show significant improvement according to the paired t-test.

For group B, the average clinical test results are presented in Table 4 in the form of the mean (±SD). The paired t-test was applied, and the significance level is indicated as bold values and a '∗' symbol on the values in Table 4. The paired t-test revealed that only the FMA-hand test ($p = 0.035$) showed statistically significant improvement for the patients in group B. Whereas, the FMA-wrist test ($p = 0.27$), MAS-hand movements test ($p = 0.423$), and MAS-advanced hand movements test did not show statistically significant improvements when the paired t-test was applied.

C. RESULTS FOR HAND-KINEMATIC PARAMETERS

The AMADEO assessment tool allows the measurement of force-flexion, force-extension, and HROM of fingers and thumb. To find the changes in these hand-kinematic parameters after the training, force-flexion, force-extension, and HROM were calculated at the pre- and post-training periods for group A and group B.

For group A, Table 5 shows the mean (±SD) values of force-flexion, force-extension, and HROM obtained at week 0 and week 4. The statistical significance levels between pre- and post-values of all three kinematic parameters were calculated using the paired t-test. The pre- and post-values of all these kinematic parameters for hand movement recovery (force-flexion, $p = 0.028$; force-extension, $p = 0.048$; HROM; $p = 0.039$) showed statistically significant improvements.

Table 6 presents the average force-flexion, force-extension, and HROM values obtained from the AMADEO assessment tool for group B. Application of paired t-test between pre- and post-values of all three kinematic parameters for group B showed that none of the improvements were statistically after four weeks of training.

VI. EXTENDED TRAINING OF GROUP B AND ITS RESULTS

Apart from the FMA-hand score, the results presented in Section V revealed that four weeks of motor training did not have a significant effect on MRCP Npeak amplitude or other clinical tests and hand-kinematic parameters' results for post-stroke patients in group B. Therefore, it was decided to extend the training period for all participants in group B for another four weeks to determine whether the extension of the hand motor training affects MRCP Npeak feature, clinical tests, and hand-kinematics parameters.

This section will describe the extended training protocols as well as corresponding assessment results for group B.

A. EXTENDED TRAINING AND ASSESSMENT PROTOCOLS FOR GROUP B

The three infratentorial stroke patients in group B underwent another phase of motor training that consisted of four weeks (12 sessions, three sessions per week) of advanced training protocols using the AMADEO device. During this extended training, patients received four levels of training each day consisting of CPM training mode for 5 minutes, CPMplus training mode for 5 minutes, Assistive training mode for 10 minutes, and Active training mode for 10 minutes. In this way, group B participants received two phases of training

TABLE 3. Average clinical tests result for group A after four weeks of motor training (mean (±SD)).

Assessment Period	FMA-Wrist Score (0-10)	FMA-Hand Score (0-14)	MAS-Hand Movements Score (0-6)	MAS-Advanced Hand Movements Score (0-6)
Pre-training (Week 0)	6.5 (±2.4)	8.3 (±2.6)	2.8 (±1)	3.3 (±2.8)
Post-training (Week 4)	**8.3 (±2.1)** *	**12 (±1.2)** *	**4.5 (±1.3)** *	4.3 (±1.5)

TABLE 4. Average clinical tests result for group B after four weeks of motor training (mean (±SD)).

Assessment Period	FMA-Wrist Score (0-10)	FMA-Hand Score (0-14)	MAS-Hand Movements Score (0-6)	MAS-Advanced Hand Movements Score (0-6)
Pre-training (Week 0)	1.3 (±1.2)	2.7 (±1.5)	0.7 (±0.6)	0.3 (±0.6)
Post-training (Week 4)	2.7 (±2.5)	**5.7 (±2.1)** *	1 (±1)	0.3 (±0.6)

TABLE 5. Average hand-kinematic parameters' results for group A after four weeks of motor training (mean (±SD)).

Assessment Period	Force-Flexion (N)	Force-Extension (N)	HROM (%)
Pre-training (Week 0)	38.9 (±14)	6.9 (±8)	52.8 (±34.9)
Post-training (Week 4)	**59.1 (±8.4)** *	**19.6 (±8)** *	**89.4 (±15.9)** *

TABLE 6. Average hand-kinematic parameters' results for group B after four weeks of motor training (mean (±SD)).

Assessment Period	Force-Flexion (N)	Force-Extension (N)	HROM (%)
Pre-training (Week 0)	15.1 (±15.9)	2.1 (±2.6)	11.9 (±18.3)
Post-training (Week 4)	31.1 (±30.3)	5.6 (±6.4)	39.7 (±34.4)

using the AMADEO device in which the second phase of training was slightly more intense compared to the first phase as it included training on active therapy. Moreover, the same three assessment procedures including EEG data analysis, clinical tests, and hand-kinematic parameters were conducted at the end of eight weeks of the designed robot-assisted training as performed during the beginning of training (week 0) and at the end of the first phase of training (week 4).

B. RESULTS OF EXTENDED TRAINING OF GROUP B

The results obtained from the data analysis of week 8 were compared to those obtained during week 0 and week 4 to measure the effect of extending the training on MRCP Npeak amplitude and physical improvements in hand motor skills. Fig. 6 shows the averaged MRCP signal plots at all eight electrodes, extracted from EEG data acquired before the beginning of rehabilitation training (week 0), at the end of the first phase of training (week 4), and after the completion of both phases of training (week 8) for infratentorial stroke patients of group B. Visual inspection of the plots reveal that averaged Npeak amplitude of MRCP signal was decreased at week 8 with respect to corresponding value at week 0 for all electrode positions (ILFC, ILC, ILCP, CLFC, CLC, CLCP, Cz, and CPz). Whereas, as stated above, the Npeak amplitude at week 4 was increased at ipsilateral electrodes (ILFC, ILC, and ILCP), slightly decreased at contralateral electrodes (CLFC, CLC, and CLCP) and CPz electrode, and remained the same at the Cz electrode compared to week 0.

To assess the significance of these variations, the MRCP Npeak feature was analyzed statistically. Fig. 7 shows the bar-chart representation of average Npeak amplitudes for all eight electrodes for group B at week 0, week 4, and week 8. A consistent decrease in average Npeak amplitude was observed for all selected electrodes after a total of eight weeks of training

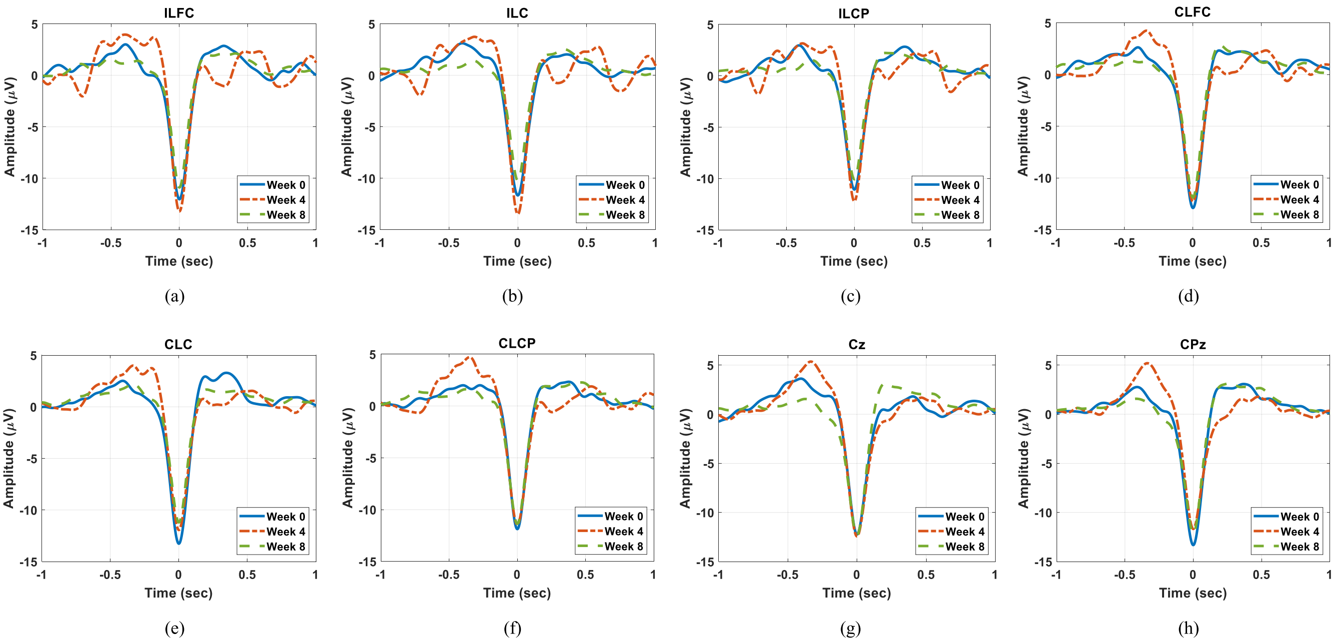


FIGURE 6. Average MRCP signals for group B at all channels after 24 motor training sessions, (a) ILFC, (b) ILC, (c) ILCP, (d) CLFC, (e) CLC, (f) CLCP, (g) Cz, (h) CPz. The legends Week 0, Week 4, and Week 8 represent the pre-training period, the post-training period 1, and the post-training period 2 respectively for group B in all figures.

TABLE 7. Average clinical tests result for group B after two-phase of training (mean (±SD)).

Clinical Tests Results				
Assessment Period	FMA-Wrist Score (0-10)	FMA-Hand Score (0-14)	MAS-Hand Movements Score (0-6)	MAS-Advanced Hand Movements Score (0-6)
Pre-training (Week 0)	1.3 (±1.2)	2.7 (±1.5)	0.7 (±0.6)	0.3 (±0.6)
Post-training 1 (Week 4)	2.7 (±2.5)	**5.7 (±2.1)** *	1 (±1)	0.3 (±0.6)
Post-training 2 (Week 8)	3.7 (±2.3)	**8 (±2.6)** *	**2.3 (±0.6)** *	1.3 (±0.6)

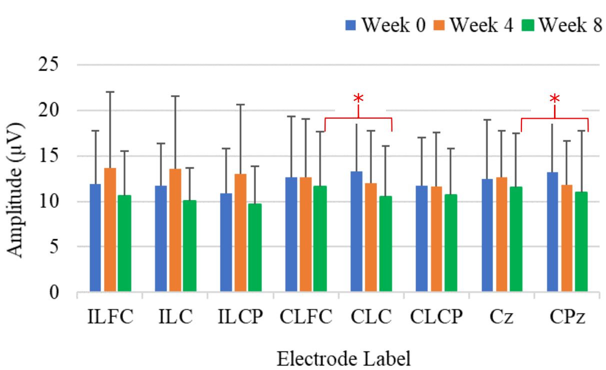


FIGURE 7. Mean absolute Npeak amplitude at Week 0, Week 4, and Week 8 for group B. The error bars represent SD values across subjects for each electrode. The symbol '$*$' indicates a significant decrease in Npeak amplitude at Week 8 compared to that at Week 0.

when it is compared with week 0. When the paired t-test was applied, a significant change in Npeak was obtained at CLC ($p = 0.01$) and CPz ($p = 0.04$) electrodes. The significance level is indicated by a '$*$' symbol in Fig. 7. In contrast to these results, change in Npeak amplitude at all eight electrodes was not consistently decreased after the first four weeks of motor training compared to week 0. These results of MRCP Npeak suggest that four weeks of rehabilitation is not a sufficient time to obtain consistent variations in EEG signal's features for the infratentorial stroke patients in group B. This outcome is consistent with clinical observations that patients with infratentorial strokes are typically slower to recover motor function than patients with supratentorial strokes [52].

Table 7 shows the average results of FMA-wrist, FMA-hand, MAS-hand movements, and MAS-advanced hand movements' clinical tests at all three assessment periods. The two-tailed paired t-test was applied between pre-training (week 0) and post-training 1 (week 4) values as well as between the pre-training (week 0) and post-training 2 (week 8) values. The results are presented in the form of

TABLE 8. Average hand-kinematic parameters' result for group B after two-phase of training (mean (±SD)).

Hand-Kinematic Parameters' Results			
Assessment Period	**Force-Flexion (N)**	**Force-Extension (N)**	**HROM (%)**
Pre-training (Week 0)	15.1 (±15.9)	2.1 (±2.6)	11.9 (±18.3)
Post-training 1 (Week 4)	31.1 (±30.3)	5.6 (±6.4)	39.7 (±34.4)
Post-training 2 (Week 8)	**42.2 (±24.9)** *	**13.9 (±6.8)** *	**64.6 (±24.8)***

the mean (±SD) and the significant change between these tests is indicated by bold values and a '∗' symbol on the values. It is observed that only the FMA-hand test shows a significant change in all patients when they complete the first phase (four weeks) of the motor training. However, after eight weeks of training, the patients show statistically significant improvement in two clinical tests i.e., FMA-hand ($p = 0.015$) and MAS-hand movements ($p = 0.038$).

Table 8 shows values for three hand-kinematic parameters which include force-flexion, force-extension, and HROM for group B during the pre-training, post-training 1, and post-training 2 periods. The values are presented in mean (±SD) and the statistical significance change is indicated by bold values and a '∗' symbol on the values. According to Table 8, none of the kinematic parameters show any significant change after motor training in the first phase (four weeks). Whereas a statistically significant improvement in all the force-flexion ($p = 0.036$), force-extension ($p = 0.041$), and HROM ($p = 0.046$) parameters were observed when the patients completed their eight weeks of training.

Clinical tests and hand-kinematic parameters' results show that group B patients regained significant motor recovery of hand functions after eight weeks of robot-assisted training and this was associated with a significant change in the Npeak of the MRCP at two electrodes sites. As mentioned before, these results match with clinical observations for this category of patients [47].

VII. DISCUSSION

The main purpose of the work presented in this article was to investigate possible changes in the features of the MRCP signal when two groups of post-stroke patients with different lesion locations receive robot-assisted rehabilitation training for their impaired hands using the AMADEO device.

The EEG data analysis revealed that all participants in both groups A and B were able to generate MRCP signals during the self-paced motor task of their affected hand at all eight selected electrode positions. The MRCP signal's Npeak was investigated for group A and group B separately to explore whether it was increased or decreased after the completion of four weeks of robot-assisted motor training. Npeak amplitude for group A showed a statistically significant decrease after four weeks of training. On the other hand, group B participants did not show a statistically significant decrease in the Npeak after four weeks. However, when the training period of group B was extended for another four weeks (a total of eight weeks), a statistically significant decrease in the Npeak amplitude at CLC and CPz electrodes was observed.

In order to determine motor and functional improvements in hand motor skills, the clinical tests, and hand-kinematic parameters were analyzed. According to the results of clinical tests obtained after four weeks of robot-assisted training, group A showed statistically significant improvement in three out of four clinical tests. Whereas group B showed improvement in only one clinical test after the first four weeks of training and two clinical tests after eight weeks of training. The analysis of hand-kinematic parameters showed that post-stroke patients in group A gained significant improvements in all force-flexion, force-extension, and HROM values after the completion of four weeks of the training program. Group B showed significant improvement in all the hand-kinematic parameters only after completing the training of eight weeks.

The reported results reveal that the Npeak amplitude of the MRCP signal was decreased consistently in patients with supratentorial strokes (group A) after four weeks of training while it was decreased consistently in patients with infratentorial strokes (group B) after eight weeks of training. These Npeak changes of both groups are also associated with improvements in clinical tests and hand-kinematic parameters' results. These results suggest that four weeks of rehabilitation is not sufficient time to induce significant MRCP signal changes for the infratentorial stroke patients who comprise group B. The clinical evidence about infratentorial stroke rehabilitation also shows that the recovery speed of such patients is slower compared to supratentorial stroke patients [52].

The decrease in MRCP Npeak amplitude after the designed robot-assisted motor training reflects those neurological pathways become more established so that fewer cortical resources are needed for motor planning and execution of tasks. This hypothesis is supported by studies in healthy participants available in the literature [20]–[24]. However, further investigations are required to validate the occurrence of neuroplasticity.

This paper demonstrates the use of the MRCP signal as an assessment tool to determine the effect of robot-assisted motor training after stroke patients gained improvement in their hand motor skills. These improvements in hand motor skills were measured by the clinical tests and hand-kinematic parameters. This means once the improvements in hand motor skills were measured using clinical tests and hand-kinematic parameters measurements, an MRCP signal was used to determine the effect of the robot-assisted training on the brain activities. EEG is an easy and cost-effective method to assess changes in brain activation during functional motor activities [24]. The results of this paper indicate that EEG has future potential in clinical utility for stroke rehabilitation.

A larger number of participants and the inclusion of a control group in the experimentation would have strengthened our confidence in the results. However, the number of potential participants was limited by the clinical availability of suitable participants within the time frame of this work. Participants in the study were relatively heterogeneous regarding the length of time from stroke to onset of the intervention (see Table 1). It may be the case that with a more homogeneous group of participants more uniform and statistically significant data could have been extracted. However, our inclusion criteria had to be broader; otherwise, clinical availability would have not allowed us to recruit a sufficient number of participants.

VIII. CONCLUSION

This paper demonstrated the feasibility of using the EEG-derived MRCP signal as an assessment parameter to determine the effect of robot-assisted motor training for stroke patients with different lesion locations. The study showed a statistically significant decrease in the Npeak amplitude of the MRCP signals for stroke patients with supratentorial lesions when they achieved significant improvements in hand-kinematic parameters and clinical test outcomes after four weeks of robot-assisted training. The infratentorial stroke patient showed a statistically significant decrease in Npeak as well as a significant improvement in kinematic parameters and clinical tests after eight weeks of the training. Hence, MRCP can be used as an assessment tool to determine robot-assisted motor training effects in both supratentorial and infratentorial strokes. Moreover, this work has real potential as a practical and inexpensive therapeutic tool that could be used by therapists to detect neuroplasticity responses during stroke rehabilitation and allow them to adjust the intensity of training challenges accordingly to enhance neuroplasticity responses and therapeutic outcomes.

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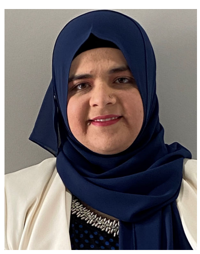

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