The effect of robot therapy assisted by surface EMG on hand recovery in post-stroke patients. A pilot study

Wpływ rehabilitacji z zastosowaniem robota wspomaganej przez powierzchowne EMG na poprawę sprawności ręki u chorych po udarze mózgu – badanie pilotażowe

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Key words
stroke, sEMG, robot-aided therapy, rehabilitation

Abstract
Background: Hemiparesis caused by a stroke negatively limits a patient's motor function. Nowadays, innovative technologies such as robots are commonly used in upper limb rehabilitation. The main goal of robot-aided therapy is to provide a maximum number of stimuli in order to stimulate brain neuroplasticity. Treatment applied in this study via the AMADEO robot aimed to improve finger flexion and extension.
Aim: To assess the effect of rehabilitation assisted by a robot and enhanced by surface EMG.
Research project: Before-after study design.
Materials and methods: The study group consisted of 10 post-stroke patients enrolled for therapy with the AMADEO robot for at least 15 sessions. At the beginning and at the end of treatment, the following tests were used for clinical assessment: Fugl-Meyer scale, Box and Block test and Nine Hole Peg test. In the present study, we used surface electromyography (sEMG) to maintain optimal kinematics of hand motion. Whereas sensorial feedback, provided by the robot, was vital in obtaining closed-loop control. Thus, muscle contraction was transmitted to the amplifier through sEMG, activating the mechanism of the robot. Consequentially, sensorial feedback was provided to the patient.
Results: Statistically significant improvement of upper limb function was observed in: Fugl-Meyer ($p = 0.38$) and Box and Block ($p = 0.27$). The Nine Hole Peg Test did not show statistically significant changes in motor skills of the hand. However, the functional improvement was observed at the level of 6% in the Fugl-Meyer, 15% in the Box and Block, and 2% in the Nine Hole Peg test.
Conclusions: Results showed improvement in hand grasp and overall function of the upper limb. Due to sEMG, it was possible to implement robot therapy in the treatment of patients with severe hand impairment.

Słowa kluczowe
udar mózgu, sEMG, terapia wspomagana robotem, rehabilitacja

Streszczenie
Wstęp: Zaburzenie funkcji ręki z powodu udaru mózgu ogranicza możliwości motoryczne chorych. Obecnie innowacyjne technologie, jakimi są urządzenia mechaniczno-elektryczne, znajdują coraz szersze zastosowanie w rehabilitacji kończyny górnej, w tym ręki. Głównym celem terapii z wykorzystaniem urządzeń robotycznych jest dostarczenie maksymalnej liczby bodźców w celu stymulowania neuroplastyczności mózgu. Zastosowana w niniejszej pracy terapia z wykorzystaniem robota AMADEO miała na celu poprawę funkcji zginania i prostowania palców ręki.

Cel pracy: Zbadanie efektywności terapeutycznej rehabilitacji wspomaganej przez robota z wykorzystaniem powierzchownego sygnału EMG.

Projekt badawczy: Badanie przed – po.

Materiał i metody: Grupę badaną stanowiło 10 osób po udarze mózgu, u których przeprowadzono terapię robotem AMADEO w liczbie co najmniej 15 zajęć. Ocenę stanu przed i po terapii sprawdzono testami: Fugl-Meyer, Box and Block test i Nine Hole Peg Test. W przedstawionym badaniu wykorzystano elektromiografię powierzchniową (sEMG) w celu zapewnienia optymalnej kinematyki ruchu ręki. Robot natomiast, dostarczając czuciową informację zwrotną, pozwalał na pracę chorego w układzie zamkniętym, kontrolowanym (*closed-loop*). Generowane napięcie mięśniowe przekazywane było poprzez sEMG do amplifikatora, który to uruchamiał mechanizm robota. Pacjent odbierał zwrotną informację czuciową w wyniku zmiany pozycji ręki.

Wyniki: Istotną statystycznie poprawę funkcji kończyny górnej zaobserwowano dla grupy badanej dla testów Fugl-Meyer ($p=0,38$) i Box and Block ($p=0,27$). Analiza wyników z testu Nine Hole Peg Test nie wykazała istotności statystycznej dla poprawy motoryki ręki. Jednakże nastąpiła poprawa stanu funkcjonalnego pacjentów: Fugl-Meyer średnio o 6%, Nine Hole Peg Test o 2% i Box and Block o 15%.

Wnioski: Badania wykazały poprawę chwytu i ogólnej funkcji kończyny górnej. Dzięki sEMG możliwe było zastosowanie robota u chorych po udarze mózgu bez aktywnego ruchu palców ręki.

INTRODUCTION

Stroke is considered one of the most common neurological diseases. It is the second cause of death in the world and the third cause of long-term disability[1]. The main problems of stroke patients are related to upper limb mobility (paresis), such as impairment in gripping that limits the activities of daily living[2]. Injured brain tissue, which disturbs nerve conduction, causes total or partial inability to selectively stimulate muscles, which, in turn, does not allow the performance of specific motor tasks[3]. Due to the fact that the upper limb is used to perform complex functional activities, such as eating, writing or manipulating/manoeuvring different types of objects, the loss of motor control of the musculoskeletal system results in severe limitations of a patient's independence. Thus, effective motor recovery of the upper limb is important in patients after stroke. Severe hand function impairment after stroke is an increasingly interesting topic within the field of neurorehabilitation and neuro-engineering technologies[3,4]. It should be noted that robotic devices can be the foundation for the work of physical therapists by implementing and properly carrying out physical tasks appointed by them. Intensive and repetitive training, with artificial feedback, which can be obtained in real-time as well as information recorded throughout each rehabilitation session, are benefits of implemented robot-aided therapy. Such devices can complement or facilitate the work of a physiotherapist, and addi-tionally, the created rehabilitation environment increases the patient's motivation to act by making the course of therapy more attractive, or by using more interesting forms of exercise (enriched even by gaming elements).

The therapeutic system of robot-aided rehabilitation is based mainly on the principles of motor re-education, which is carried out through isolated sensory-motor and task-oriented exercises. In this aspect, the learning process means re-acquisition of motor skills after various types of injuries to the central nervous system (CNS). The main role is not played by the movement itself, but by focus on the purpose of its implementation, because the process of motor learning is facilitated when there is external stimuli[6]. Therapies based on robotic devices allow from 2 to 7 times more movements than conventional therapy[7]. It is also of great psychological significance because therapy provides positive reinforcement for successful movement sequences. However, simply repeated exercises cannot be considered in motor function learning because they are not the only factor promoting reorganization of the cortical area. Movements must be characterized by appropriate activity, intensity and specific task-orientation[8,9].

Innovative technologies help to restore loss of motor functions, usually in combination with traditional therapy. Robot-aided therapy has already found wide practical application. It owes its effectiveness to the basis of sensorimotor integration combined with multi-sensory feedback (auditory, visual, sensory)[10,11]. By strengthening the stimuli and creating conditions for intensive training of active, assisted and passive exercises, robots become a great tool in intensifying therapy. The action of robots is mainly based on the use of assisted exercises, which makes it possible for the patient to complete the initiated movement. The innovativeness of robot-aided therapy presented in this study consists in the application of surface electrodes for real-time electromyographic signal aquisition, coming from the finger extensors and flexors. Thus, an active and assisted exercises were used in patients with no finger movement.

The aim of the study was to evaluate the therapeutic effectiveness of robot-aided rehabilitation enriched by surface electromyography (sEMG).

RESEARCH MATERIAL AND METHODOLOGY

The study group composed of patients who underwent rehabilitation with the AMADEO robot in the number of at least 15 completed sessions, no later than 2 years after the stroke. Ten post-stroke patients were examined, including 8 after ischemic stroke and 2 after hemorrhagic stroke. There were 8 males and 2 females in this group. The brain injury affected various areas, as follow: parietal lobe, posterior-right temporal bulbar tract, right-side spinal cord bulbs, lenticular nucleus, thalamus, temporo-parietal region, as

well as the central and temporal arteries. Only two patients were diagnosed with mild aphasia, but no cases of apraxia were found. The age of the patients enrolled in the study ranged from 53 to 81 years, setting its average age at 71.01 ±10.20. The mean time from onset of stroke was 6.94 ±6.80 months.

The patients included in the study underwent 30 minutes of training for at least 15 treatment sessions with the AMADEO robot (Tyromotion GmbH Graz, Austria). In order to facilitate execution of the given tasks, surface electrodes were placed on the flexors (flexor digitorum profundus) and extensors (extensor digitorum, extensor digiti minimi) of the fingers which enabled reading the electromyographic signal from surface electrodes (sEMG) (Figure 1).

ergy. The test assesses the functioning of the wrist and hand, where the flexion and extension of the fingers as well as individual grabbing movements are assessed in the proximal part of the upper limb. Coordination and movement speed are analyzed. A maximum of 66 points can be obtained. The Box and Block test measures two-sided manual efficiency. The patient's task is to move (taking into account the partition between chambers) as many blocks as possible (150 overall) from the first to the second chamber in 1 minute. Then, the task is repeated by the healthy limb. The Nine Hole Peg Test (NHPT) is used to assess hand function, administered by asking the patient to take the pegs from a container and, one by one, place them in holes on a board (maximum of 9) as quickly as possible and

the Ethics Committee to conduct the experiment (Protocollo 2014.14 sERF).

The study group consisted of patients from the IRCCS Fondazione Ospedale San Camilloscientific institute in Venice (Italy). The study included patients who experienced both hemorrhagic or ischemic stroke, at least two years before starting rehabilitation with AMADEO. The patients with spasticity, traumatic injuries, retractions, apraxia, motor aphasia, epilepsy, neoplasm, hemianopia or skin lesions near the electrodes, were not included in the study. The non-parametric Wilcoxon test was used to evaluate changes before and after the therapy. Statistical significance was determined at the level of $p \leq 0.05$.

Figure 1
Placement of electrodes on the flexors and extensors of the right hand fingers

The patients, whose ability to overcome the resistance due to the flexion and extension movement of the fingers was disturbed while muscle activity was preserved, were tested. The tests were performed using the following evaluation tools: Fugl-Meyer test for the upper limb (FM), Box and Block test and Nine Hole Peg Test (NHPT). The FM test concerns sensory-motor assessment of the upper limb. This scale is divided into 9 parts, including muscle reflex evaluation of the forearm biceps and triceps muscles, flexion and extension synergy of the entire limb, movements with and without muscle syn-

to pull them out and put them back in the container. Each hand is assessed separately on the basis of the time needed to complete the task. The test allows to determine finger dexterity – this test requires a more precise grip to be performed than in the case of the Box and Block test.

The tests were performed before (PRE) and after completing (POST) therapy using the AMADEO robot. A protocol with a personal questionnaire was used to archive clinical data. Patients signed informed consent to use the results from their examination for scientific purposes. The study obtained permission from

Description of robot-aided therapy by use of the AMADEO and sEMG

One therapy session with the AMADEO robot lasted approximately 1 hour (h), including all the necessary steps needed to prepare and protect the patient as well as the robot itself. The patient was seated opposite the robot in a comfortable but corrected position (Figure 2).

When the patient assumed the proper position, magnets were attached to his/her fingers and then connected to the mobile units of the robot (Figure 3).

The elbow joint of the subject was set in flexion at 90°, and the wrist was immobilized by a band with Velcro in neutral position. When the patient was prepared to start therapy, the physiotherapist first determined the range of motion (ROM) of the fingers. The ROM was subjected to modification depending on the changes taking place within the patient. The robot was then calibrated with the EMG amplifier. After reading the basic signal, i.e. the initial value of the muscle signal at rest (baseline), the threshold of muscle activity was determined. Establishing baseline is necessary because it allows to determine the threshold of stimulation, which usually constituted 30%
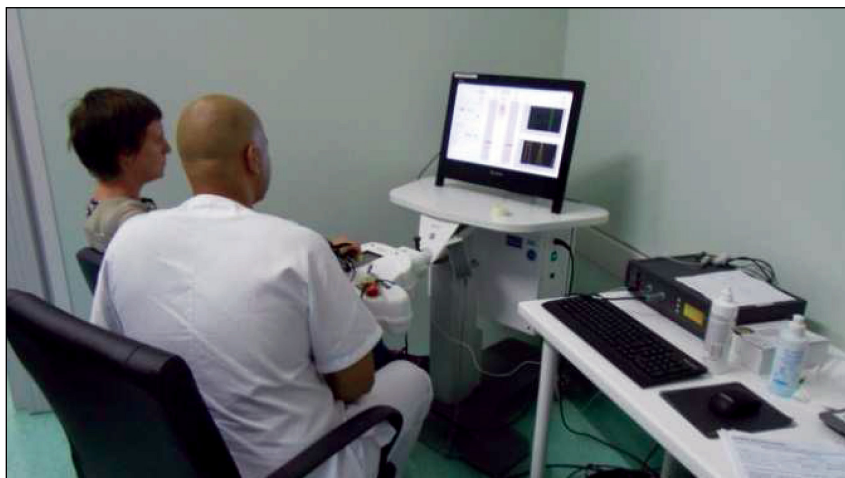
Figure 2
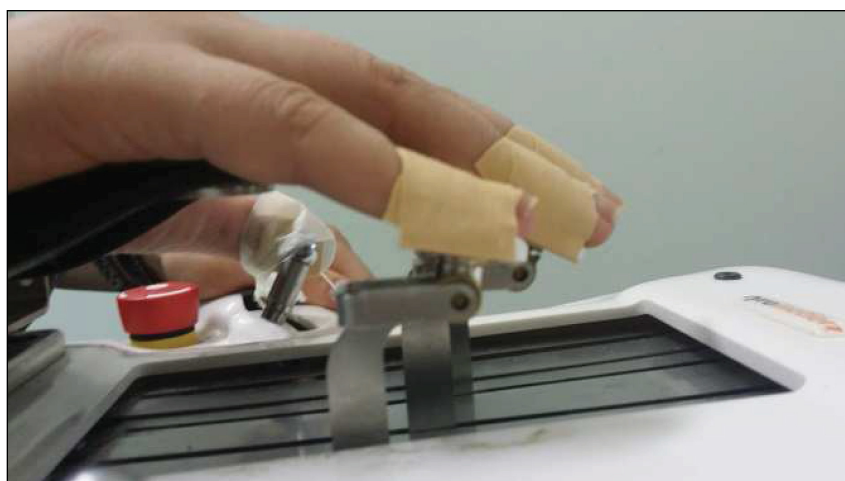**Therapeutic unit using the AMADEO robot**

Figure 3
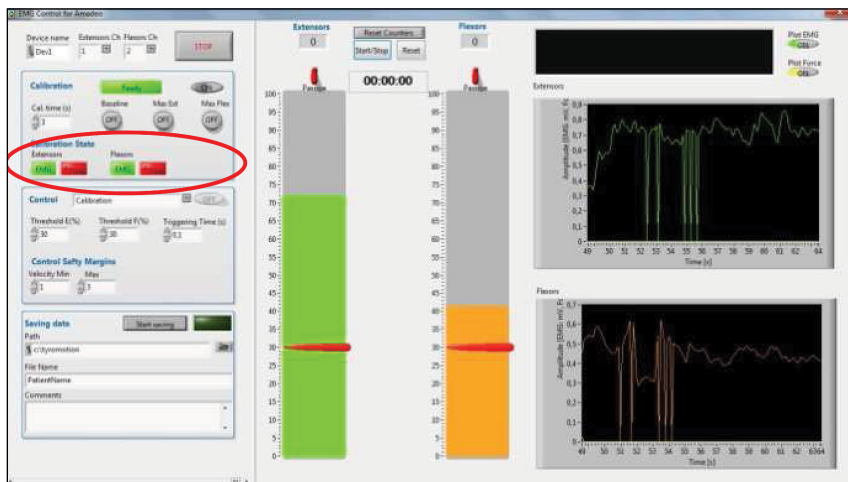**Attachment of magnets to the right hand during therapy using the AMADEO robot**

Figure 4
Calibration – maintained muscle nerve activity (green for the extensor and flexor EMG icons) and lack of generated force (red for the Extensor and Flexor Force icons)

of the maximum value obtained during intentional muscle contraction. Exceeding this value determines the work of the robot, because the robot will start its movement only after the generation of appropriate stimulus.

Therefore, calibration is a part of the therapy. Thanks to the use of sEMG, subjects without active hand movement were included in the presented therapy (Figure 4).

The first proper stage of the therapy was the warm-up. The patient did not have to generate strength or focus on the movement. The essence of this stage was patient's familiarization with the robot. The next part required active participation of the patient - activation of the extensors and flexors. Both stages appear to be similar, however, in one part, the patient had to control the muscles of the finger extensors, and in the next, the flexors using the EMG signal. The robot, on the other hand, performed passive return movements. Then, active finger flexor movement were performed (flexor control). During the next stage, the robot performed passive flexion of the fingers with active movement of extensors (extensors control). The movements performed by the patient at this stage were so simple that it was enough to initiate the movement, and later the AMADEO robot helped complete the effort. At this stage, the initiation of movement is only affected by the generation of muscle tension, which exceeds the set threshold to initiate movement, regardless of whether the antagonistic group of muscles was also, simultaneously stimulated. This occurs in order to prepare the patient for further stages of therapy, when isolated movement is more desirable. The number of performed repetitions was counted automatically.

The next stage of therapy was control of both muscle groups - the finger extensors and flexors. Both phases, flexion and extension, forced the patient to perform isolated movements. The next step was so-called EMG threshold based control. At this stage, the patient had to generate a signal that exceeded baseline, but unlike previous stages, the robot did not complete the initiated motion after detecting one impulse. The muscle tension had to be continuous to complete the ordered motor task. The final stage of the training was the control of the difference in electromyographic signal (EMG difference

based control). At this stage, the patient was tasked with controlling the isolated flexion and extension movement of the fingers so that the difference in extensors activity with respect to the flexors was at least 10%.

The stages represent a closed-loop paradigm, which began when the patient, focused on the performance of a specific motor task, caused muscle tension. At this moment, the stimulus read by sEMG is properly processed and changes the position of the patient's hand. The initiated movement becomes a feedback for the patient who sees the movement. Movement of the hand by the robot, provides sensory feedback that is directly related to the change in position of the distal part of the upper limb. The patient, feeling the change in hand position, can monitor it through signal strength values presented on the monitor. Visual feedback represents muscle strength and allows the patient to better improve muscle control. Closure of the closed-loop system occurs with the initiation of another movement and when enriched with information about previous movement[12].

Description of the AMADEO robot

The AMADEO robot (Tyromotion GmbH Graz, Austria) is a device that can be considered as an external manipulator for upper limb exercise, especially considering exercises for the finger flexion and extension. This robot provides properly selected training in combination with the intense frequency of repetitive exercises aimed at improving grip ability. The training programme is determined by a physiotherapist, who adjusts the intensity of exercises combined with the visual feedback displayed on the monitor. The AMADEO robot supports flexion and extension movements of the fingers, it has four longitudinally moving units from the patient's perspective and two directing movements transversely (for the thumb). All mobile robot units are independent and allow movement in almost all of its possible ranges[2]. The AMADEO robot allows to individually modify settings for each patient. Depending on the degree of injury and disability, the level of difficulty of the exercises is adjusted by the physiotherapist. Passive exercises allow for passive movement by performing a proper movement pattern. The active-assisted movements are initiated by the patient and terminated by the robot. Adding the signal from sEMG to the AMADEO robot enables rehabilitation for patients with serious injuries and motor defects in which hand movement is significantly reduced. This modern combination provides the opportunity to extend the range of patients who can benefit from this device. In this case, the essence of the AMADEO robot is to strengthen the electrical signal generated in the contracting muscles to be able to reflect neuromuscular activation.

This is done thanks to the surface electrodes placed on the patient's forearm that transmit pulses to the amplifier. This, in turn, processes and sends them to AMADEO. sEMG allows simple access to the physiological process that generates compressed muscle force along with the right movement. Using the EMG signal in the AMADEO robot allows to capture even the weakest impulses indicating muscle activity, and thanks to that, it is possible to rehabilitate patients with preserved nerve activity but without proper muscular strength. Due to the appropriate setting of parameters by the physiotherapist, minimal muscle activity causes cooperation with the robot, i.e. moving the fingers (flexion and extension)[13].

RESULTS

The non-parametric Wilcoxon test was used to analyse the "before-and-after" values of therapy, while the remaining values were calculated using Microsoft Excel.

The group included 10 subjects after stroke who underwent rehabilitation with the AMADEO robot. The evaluation of their condition before and after therapy was evaluated using the following tests: Fugl-Meyer, Box and Block and the Nine Hole Peg Test.

Statistically significant improvement in upper limb function was observed in the Fugl-Meyer ($p=0.38$) and Box and Block ($p=0.27$) test groups. Analysis of results from the Nine Hole Peg Test did not show statistical significance of the improvement in hand motor ability.

The obtained results indicate improvement in the upper limb function in the three tests used. The greatest improvement was observed in the Box and Block test, which exceeded the level of 15%.

The Fugl-Meyer test for the upper limb showed average improvement by 6% in the study group. On the other hand, the Nine Hole Peg Test showed improvement at the level of 2%. The obtained results are illustrated in Table 1.

Table 1

Functional tests	Study group		Statistical values
	Before	**After**	
FM	40.1 ±19.6	44.3 ±18	0.038*
NHPT	2 ±2.87	2.2 ±3	0.593
Box&Block	4.4 ±13.9	16.8 ±16.4	0.027*

Assessment of upper limb motor ability before and after application of therapy using the AMADEO robot

FM –Fugl-Meyer test for the upper limb; NHPT – Nine Hole Peg Test; Box&Block – Box and Block test.
Before – functional test results of the study group before starting therapy; After – obtained results after completion of physical therapy using the AMADEO robot.
* Statistical significance of therapy (p≤0.05); Wilcoxon test.

DISCUSSION

Therapy with the AMADEO robot is an innovative method, focusing solely on improving hand function. The results obtained from the conducted study indicate general improvement of upper limb function with the use of robot-assisted therapy. This therapy is intended for people with a severe gripping function disorders measured by the Box and Block and NHPT tests. The results showed that in the NHPT, the patients were able to perform the task of placing the pegs in the appropriate location only twice. Here, the improvement was only 2%, and solely in this situation was statistical significance not shown. This may be related to the fact that NHPT evaluates the most precise grip, requiring high motor skills of the hand. Greater effects were noted by assessing the less precise grip with the Box and Block test. Before therapy, the patient was able to move about 4 blocks from one box to another in 60 seconds, while after the therapy, the number of moved blocks increased to about 17 in 60 seconds, on average. This test requires advanced motor control of the upper limb, while the grip function does not have to be precise as in the case of the NHPT test. Therefore, the reported improvement was clinically significant. In the case of functional assessment of the upper limb (Fugl-Meyer), positive effects were noted. Patients with moderate limb damage (approximately 40 points) who statistically improved their motor functions (on average, about 4 points) were included in the study. According to the obtained results, no minimal detectable change (MDC - the smallest statistically estimated change, which can be detected by measurable tests corresponding to changes in the patient's ability) was observed in the tests. It is the minimal detectable change in the patient's results that guarantees that the change is not a result of measurement error. MDC determines the confidence interval, e.g. MDC95 is based on 95% confidence interval. The values obtained for the Box and Block test were close to the MDC threshold - the minimum value was 18%, the test

result was 15%. Also in connection with the Fugl-Meyer test, the values obtained in the study were close to the MDC (result of about 4 points, and the threshold of 5.2 points).

The brain tissue injury which alternates sensory-motor connectivity within cortical areas causes total or partial inability to selective muscles activation, and this, in turn, inhibits specific movements. Thus, the therapy should be implemented as soon as possible and should be characterized by an individual approach to the patient. The most important factors affecting faster patient recovery are intensity, duration and repetition. In addition, it has been proven that the type of therapy is less important than its intensity[3]. In a very easy way, the AMADEO robot provides precisely this type of exercise, allowing modification in type and level of difficulty. The nervous system is stimulated to reorganize affected areas and/or change movement functions by stimulating fingers and hand movements. In neurorehabilitation, great attention is paid to the use of early, intense, repetitive and adapted exercises. The AMADEO robot allows to provide a variety of movement tasks, increasing the difficulty of completing the exercise, or by focusing on stimulating a specific muscle group. Undoubtedly, the supportive element of the AMADEO robot is the addition of surface electrodes and the transformation of the electrical signal generated in the muscle fibres. This is an innovative approach to the problem of post-stroke rehabilitation with the use of robotic devices, and so far, no studies have been conducted describing the extension of AMADEO's work in this way. sEMG is a non-invasive method measuring muscle electrical activity that arises during contraction and relaxation. An unprocessed EMG signal provides only information allowing to determine whether the muscle is electrically active and can generate strength. Proper processing of the received signal becomes the source of much data, such as burdening or fatigue of the examined muscle.

In a study by Sale et al., intensive training with the use of robotic devices

in patients in acute condition has been shown to contribute to a significant reduction in disability and motor disorders in relation to hand rehabilitation[2]. These authors stated that intense training of grabbing movement especially stimulates the brain for motor re-education. The training included intense task-oriented exercises. They also draw attention to the possibilities for further development of robotics in rehabilitation by adding to EEG or EMG devices, which would facilitate the quantitative and qualitative evaluation of its effects[14]. Research by Colombo et al., however, show that upper limb therapy supported by the AMADEO robot provides positive effects of motor re-education and reduces general disability[15]. Scientific evidence also emphasizes the importance of brain plasticity in the neurorehabilitation process due to the possibility of cortical reorganization. The positive influence is visible in the case of early, intensive and repetitive therapy as an optimal model of rehabilitation minimizing motor deficits and supporting motor re-education[14,16,17].

Conclusions

The conducted study showed that robot-assisted rehabilitation can have a positive effect on upper limb functional improvement. Therapy with the AMADEO robot assisted by with sEMG allows for rehabilitation in patients after stroke with severe motor deficits in the hand.

Conflict of interest
The authors declare that they have no competing interests.

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