Research article/Raziskovalni prispevek

COGNITIVE-FEEDBACK TRAINING OF HAND FUNCTION IN PATIENTS AFTER STROKE

KOGNITIVNO URJENJE FUNKCIJE ROKE PRI OSEBAH PO KAPI

Gregorij Kurillo[1], *Nika Goljar*[2], *Tadej Bajd*[1]

[1] Faculty of Electrical Engineering, Laboratory of Robotics and Biomedical Engineering, University of Ljubljana, Tržaška 25, 1000 Ljubljana

[2] Institute for Rehabilitation, Republic of Slovenia, Linhartova 51, 1000 Ljubljana

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Key words: *grasping; grip force; hand rehabilitation; stroke; tracking*

Abstract – Background. *Several investigators have shown beneficial effects of cognitive feedback training on the rehabilitation progress of stroke patients. The repetition of different visually guided motor tasks can initiate the relearning process inside the central nervous system.*

Methods. *Force tracking method was used for the training of grip force control with the aim to possibly improve the ability to balance and release the grip. The tracking system consisted of two force-measuring units of different shapes, which were connected to a personal computer for data acquisition and visual feedback. In our preliminary study the training method was applied as a supplemental therapy for 10 post-stroke patients who trained over a period of four weeks.*

Results. *Most of the patients showed visible improvements in the overall accuracy of tracking. The tracking results show improvements in the tracking error, grasp stability and release of the grip. The results indicate the largest improvements in the patients who had some, yet greatly reduced grip force control.*

Conclusions. *The results suggest that the cognitive feedback associated with repetitive motor performance in the tracking task can have beneficial effect on rehabilitation process with the aim to improve finger coordination and grip force control.*

Ključne besede: *prijemanje; sila prijema; rehabilitacija roke; možganska kap; sledenje*

Izvleček – Izhodišča. *V pričujoči preliminarni raziskavi smo želeli ovrednotiti metodo sledenja kot terapevtski pripomoček za urjenje funkcije roke pri osebah po kapi. Številne predhodne študije so pokazale pozitiven učinek ponavljajočega izvajanja različnih nalog ob posredovani vidni povratni informaciji. Pri ponavljanju različnih motoričnih nalog lahko pride do reorganizacije osrednjega živčnega sistema in s tem do izboljšanega nadzora motoričnega odziva mišic. Uporaba računalniško podprte rehabilitacije ima prednost pred klasičnimi metodami, saj omogoča sprotno in bolj objektivno spremljanje rezultatov, ki jih lahko posredujemo tudi pacientu.*

Metode. *Izdelali smo merilni sistem za merjenje sile prijema, ki je bil v povezavi z osebnim računalnikom uporabljen za urjenje funkcije roke z metodo sledenja. Merilni sistem sestavljata dve merilni enoti v obliki valja in tanke plošče. Oseba je morala s silo prijema slediti različnim tarčam, prikazanim na računalniškem zaslonu. Največja vrednost tarče je bila samodejno nastavljena na 30% bolnikove maksimalne sile prijema, ki je bila vsakokrat izmerjena pred urjenjem. S tem je bila naloga prilagojena pacientovim trenutnim sposobnostim. Naloge sledenja so bile ob sodelovanju fizioterapevtov načrtane s ciljem povečevanja mišične jakosti, izboljšanja upravljanja sile ter izboljšanja odpiranja prijema. Izdelan je bil tudi programski vmesnik s podatkovno bazo, ki omogoča samodejno shranjevanje rezultatov urjenja. V raziskavo je bilo vključenih 10 oseb po kapi, ki so se urili vsak dan v obdobju štirih tednov. Osebe so bile v času urjenja z metodo sledenja vključene v program običajne delovne terapije. Urjenje so samostojno izvajali delovni terapevti.*

Rezultati. *Po štiritedenskem urjenju z metodo sledenja smo opazili znatno izboljšanje v sposobnosti upravljanja sile prijema pri osmih od desetih oseb. Največje zmanjšanje napake sledenja je bilo opaženo pri sinusni nalogi. Povečanje stabilnosti sile ter zmanjšanje tremorja pa je bilo vidno pri rampi in pravokotnem signalu. Osebe, ki v začetku treninga med sledenjem niso mogle doseči 30% jakosti prijema, so po koncu treninga lahko dosegle vse nivoje tarče.*

Zaključki. *Iz rezultatov študije ugotavljamo, da bi bila predlagana metoda sledenja primerna za urjenje koordinacije prstov in upravljanja sile prijema. V prihodnosti bi bilo potreb-*

no izvesti obsežnejšo študijo ter rezultate primerjati z rezultati nekaterih ustaljenih kliničnih metod (npr. motorični test po Fugl-Meyerju).

Introduction

Each year 750,000 people in the United States and nearly one million people in Europe are affected by stroke (1, 2). Due to the complexity of the central nervous system injuries and the number of patients, the therapy of stroke survivors represents one of the most challenging tasks in rehabilitation (3). The majority of post-stroke patients have initial paralysis of the arm and leg on one side of the body decreasing the ability to perform different activities of daily living (4). The rehabilitation of patient's hand is focused on the restoration of the affected sensory-motor functions through repetitive functional tasks (5). The rehabilitation should include intensive training of different muscle groups for recovery of the sensory-motor system and to possibly achieve the long-term effects (6).

Different researchers have shown that the effects of therapy can be further improved by introducing cognitive feedback to a patient (7, 8). The cognitive feedback can be presented to the patient in the form of video or audio information or tactile stimulation, either after each session or in real time during the therapy. The repetition of different motor tasks can initiate the relearning process inside the central nervous system and contribute to the improvement of functionality of the affected muscles (9). Functional performance can be increased by constraint induced movement therapy (10) where the less-affected limb is restrained while the affected limb is lead through different exercises which also include target tracing. In a similar way computerized tracking tasks (11) can be used for the assessment and training of the sensory-motor functions. In the tracking task a person applies the force or executes movement according to the visual feedback while minimizing the difference between the target and the actual response. By selecting the appropriate dynamic properties and amplitude of the target, patient's therapy can be efficiently controlled (e. g. training of the grip release, training of the maximal grip force). During the repetitive tracking the patients try to improve their performance to achieve better results while contributing in this way to the rehabilitation process (7). The advantages of the computer supported rehabilitation under the supervision of the therapist are mainly in much richer selection of different tasks (e. g. use of virtual environments [8]), greater repeatability of the tests and more accurate measurements (4). The measured data of each training session are used for the quantitative evaluation of the rehabilitation progress.

The tracking method as a rehabilitation therapy was presented by Kriz et al. (7) showing the positive influence of such therapy on the restoration of the grip force control in patients after traumatic brain injury. The tracking tasks have also been used to study the development of grasping in children (12). Positive influence of visual feedback on the grip force control in patients with Parkinson's disease was shown by Vaillancourt et al. (13). The tracking method was also used to evaluate grip force control in patients with different neuromuscular diseases (14). In this paper we present tracking-based training method which could be used to improve the accuracy of the grip force control and enhance the ability to balance and release the grip. In patients after stroke the ability to control and scale grip forces is greatly reduced (15, 16). Restoration of the grip strength and force control is therefore one of the most sensitive assessment scores of upper limb recovery (17).

Methods

Grip force tracking system

The tracking system consists of two grip-measuring devices of different shapes (cylinder and thin plate) which connect to a personal computer through an interface box (Figure 1). Each grip-measuring unit is based on a single point load cell (PW6KRC3 and PW2F-2, HBM GmbH, Darmstadt, Germany), which is mounted on a metal construction. The design of the devices was based on our previous research (14). The shape and the size of the measuring objects are similar to the objects used in daily activities, allowing in this way the assessment of functional gripping forces. The measuring unit in the shape of a glass allows the assessment of forces up to 300 N (equivalent mass of about 30 kg) with the accuracy of 0.02% over the entire measuring range. The second device is made up of two metal parts which shape into a thin plate at the front end, resembling a flat-shaped object (e. g. a key). The unit can measure forces up to 360 N (36 kg) with the accuracy of 0.1%.

Figure 1. *A compact assessment system with two different measuring objects in the shape of a cup and thin plate can be connected to a personal computer to accurately measure the dynamic grip force in cylindrical and lateral grip.*

Sl. 1. *Merilni sistem za merjenje sile prijema z dvema objektoma v obliki kozarca in tanke plošče omogoča merjenje časovnega poteka sile različnih prijemov (npr. cilindričnega in lateralnega prijema) z osebnim računalnikom.*

The output from the two load cells is sampled through the interface box, consisting of an amplifier with supply voltage stabilizer and integrated 12-bit A/D converter. The interface box connects to the parallel port of a personal computer, which is used for data acquisition and visual feedback. The force signal was sampled with the frequency of 100 Hz and filtered in real time by the 2^{nd} order Butterworth filter (cut-off frequency 12.5 Hz, delay 80 ms). The rehabilitation system for the training of grip force control based on the tracking task is presented in Figure 2 (below). The goal of the tracking task was to apply the grip force according to the visual information from the computer screen which was presented to the patient. The measured response was then analyzed to evaluate patient's performance during the period of training. The tracking tasks, data acquisition and the database of patients were programmed in Matlab-Simulink (The MathWorks, Inc., Natick, USA).

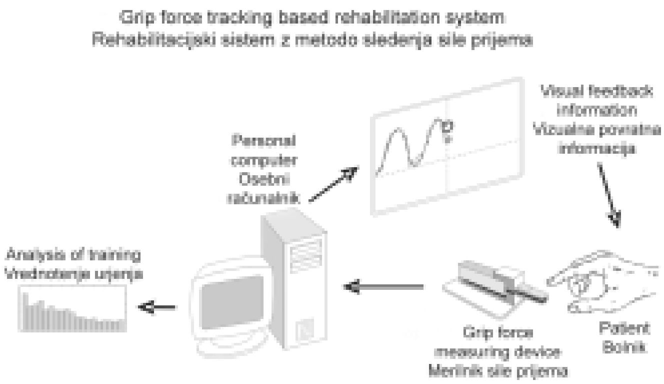

Figure 2. *The aim of the training with the tracking system was to track the presented target as accurately as possible by applying the appropriate force to the grip-measuring device. The performance was evaluated by the tracking error between the target and measured response. The patients were trained with four different tasks: the assessment of maximal grip force, tracking of a randomized ramp and step signal and a sinus signal with the changing frequency.*

Sl. 2. *Pri urjenju z metodo sledenja bolnik s prilagajanjem sile prijema na merilni senzor sledi različnim tarčam prikazanim na računalniškem zaslonu. Sposobnost upravljanja sile prijema se ocenjuje z napako sledenja, ki izraža razliko med izmerjenim potekom sile ter tarčo. Bolniki so se urili s štirimi različnimi nalogami: merjenje maksimalne sile, sledenje naključne rampe in pravokotne tarče ter sledenje sinusne tarče s spremenljivo frekvenco.*

Participants

Ten patients after stroke, 4 female and 6 male, ages 19 to 79, participated in this investigation (Table 1). Four of the patients had a left-side hemiparesis and the other six had a right-side hemiparesis. The time between the onset of the condition and the training was between 1 to 6 months for most of the patients. The patients were all attending regular occupational therapy program and were considered to be rehabilitated to a large extent. Prior to the investigation, all patients were informed of the training procedures and gave consent to participate. The study was approved by the ethics committee of Institute of Rehabilitation, Republic of Slovenia.

Training

Two different visual representations of the tracking tasks were used for the training. For the assessment of the maximal grip strength a blue bar with the height proportional to the applied grip force was presented on the screen. When the force was applied to the measuring object, the height of the bar increased in real time. Simultaneously a green mark indicating the value of the grip force as obtained in the previous trial was shown. If the patient applied a higher force, the blue bar pushed the green mark to a new position. If the patient was unable to reach the target force of the previous trial, the target of the next trial was set at the force level the patient could reach. The information on the previous performance was indicated to encourage patients to try to improve their grip strength from the previous day.

Table 1. *Ten post-stroke patients were trained with the grip force tracking system over a period of 4 weeks (M – male / F – female; R – right / L – left).*

Razpr. 1. *V štiritedensko urjenje funkcije roke z metodo sledenja je bilo vključenih 10 oseb po kapi (M – moški / Ž – ženska; D – desna, L – leva).*

Patient Bolnik	Age Starost	Gender Spol	Hemiparesis Hemipareza	Time since onset Čas od kapi	Grasp trained Prijem
P1	28	M M	R D	19 months 19 mesecev	lateral lateralni
P2	20	M M	L L	6 months 6 mesecev	cylindrical cilindrični
P3	19	F Ž	R D	1 month 1 mesec	cylindrical cilindrični
P4	44	M M	R D	1 month 1 mesec	lateral lateralni
P5	43	F Ž	L L	4.5 months 4,5 meseca	lateral lateralni
P6	49	M M	R D	3 months 3 meseci	lateral lateralni
P7	51	F Ž	R D	6 months 6 mesecev	lateral lateralni
P8	36	F Ž	R D	6 years 1 mesec	cylindrical cilindrični
P9	72	M M	L L	1 month 1 mesec	cylindrical cilindrični
P10	79	M M	L L	4 months 4 meseci	cylindrical cilindrični

The second task required the patient to track a changing target by applying appropriate force to the grip-measuring device. The target signal was presented with a blue ring moving vertically in the centre of the screen. The applied force measured with the grip-measuring device was indicated with a red spot. When the grip force was applied, the red spot moved upwards and when the force was released, the red spot moved to the initial position (Figure 2). The aim of the task was to continuously track the position of the blue ring by dynamically adapting the grip force to the measuring object. Three different tracking signals were used for the training of grip force control: randomized ramp and rectangular signals and sinus signal with the increasing frequency (Figure 3). Periodic signals were avoided not to reduce patient's attention span. The signal values included levels reaching up to 30% of the patient's maximal grip strength to maximize patient's performance during each session. The selection of signal properties was made by the occupational therapists.

The patients trained with the affected side for about 15 minutes daily, 4–5 times a week for four weeks. The progress of the rehabilitation was evaluated by calculating relative tracking error (rrmse) between the target signal and the measured force response over the trial time (11). Paired-samples t-test was used to compare the differences in the performance at the beginning and the end of training for each patient. We considered P-values of 0.05 or less as statistically significant. Logarithmic regression was used to analyze the performance trends of the daily tracking results of each patient. The unaffected side was tested once every week to obtain reference results of each individual. The training sessions were supervised by a physical therapist. During the period of training with the grip force tracking system all the patients received standard rehabilitation exercises.

Results

Figure 3 shows the results of the grip force tracking for one arbitrary selected patient (P6) from the group of patients who

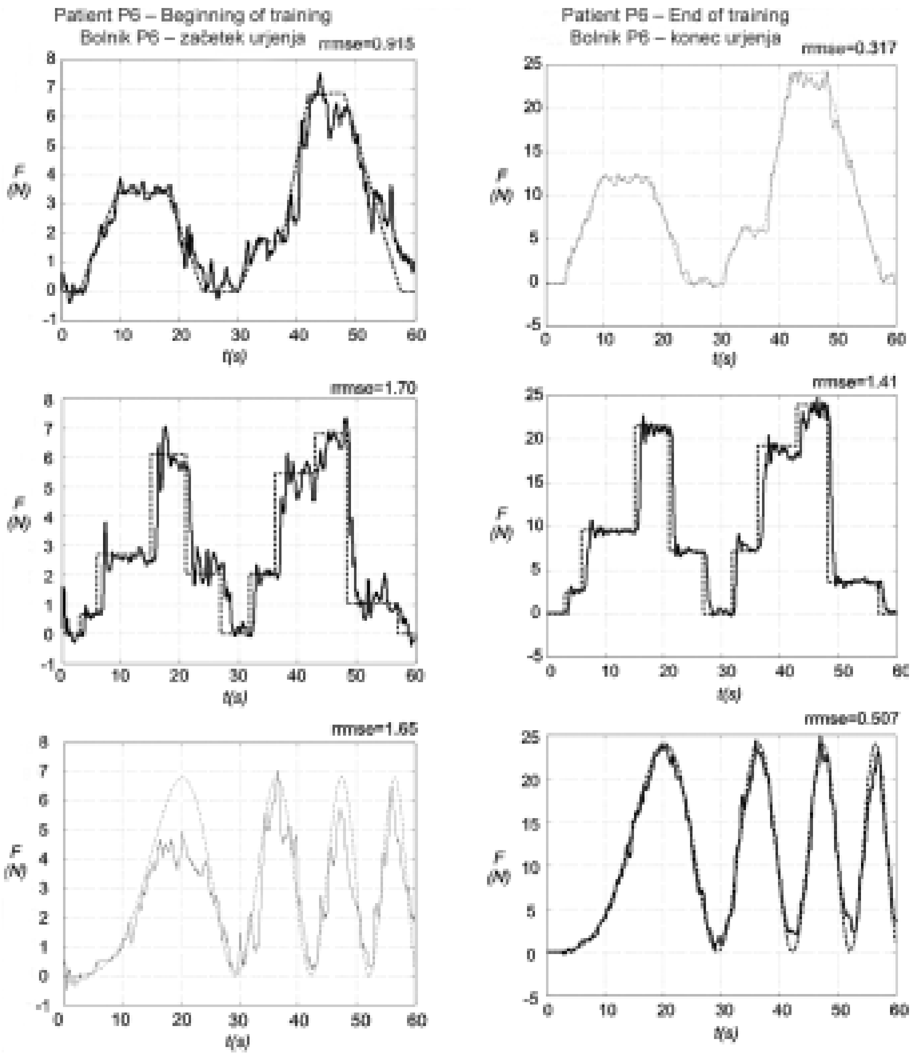

Figure 3. *The results of the measured force of the three tracking tasks as compared between the beginning and the end of the training period in one of the patients after stroke. The tracking results show significant improvements in the grip force control after the training with the tracking system.*

Sl. 3. *Rezultati izmerjene sile pri treh različnih nalogah sledenja, ki so bili pridobljeni na začetku (levo) ter na koncu kognitivnega urjenja (desno) pri enem od bolnikov. Rezultati kažejo na znatno izboljšanje v upravljanju sile prijema po urjenju z metodo sledenja.*

considerably improved their tracking performance during the four-week training. In the results the performance of the three tracking tasks at the beginning and at the end of the training period is compared. In the ramp task (Figure 3, above) the patient had difficulties keeping the grip force stable when the signal was levelled. When the target was decreasing he was unable to release the grip completely. After the training the patient was able to perform the task with much greater accuracy. The tracking error decreased for about three times (from 0.92 to 0.32). The produced output force was smoother with better stability during the constant phases of the signal. The patient also improved the release of the grip and increased the maximal grip strength.

Comparing the results of the step task (Figure 3, centre) shows that the patient improved the ability to stabilize the grip force after the training. Overshooting of the target by applying too much force is evident at the beginning of the training and is resulting in low accuracy of tracking (rrmse = 1.70). At the end of the training the patient was able to track the target more accurately (rrmse = 1.41) and produced a smooth response. The grip force control of the affected hand was improved for both, the application and the release of the grip.

The results of the sinus task (Figure 3, below) show that the patient was unable to smoothly increase and decrease the grip force at the beginning of training which resulted in more abrupt grip force response producing a large tracking error (rrmse = 1.65). The patient was incapable to track the signal during the peak phases of the sinus. After the training the patient considerably improved the performance and reduced the tracking error for more then three times (rrmse = 0.51).

Figure 4 shows the tracking results in the ramp task as assessed daily in the affected side (above) and once a week for the unaffected side (below). For clarity of the diagram only the results of the patients who showed significant improvements in this task are presented. The results of the patients P8 and P10 are excluded from Figure 4 due to the large variability. Logarithmic regression curve was applied to analyze the trends of the performance in each patient (Figure 4, above). Comparing the results of the affected side with the unaffected side shows that all patients considerably reduced their tracking error during the four weeks of training to the levels as assessed in their unaffected side. Weekly assessment was not done for patient P4 due to his inability to perform the grip with the contralateral hand. Only small improvements were evident in the patients P1 and P3 who performed the task with good accuracy from the beginning of the training. For the unaffected side only smaller changes in the tracking accuracy were noticeable after the first week of training (Figure 4, below).

In Figure 5 the results of the training of all patients are presented for the maximal grip force (above) and the tracking error as assessed in the ramp task (below). The results show the average scores as obtained during the first five and the last five training sessions. For each patient we tested if the difference in the performance between the beginning and the end of training was significant (paired-samples t-test). The results of the first task show that 7 patients improved their maximal grip force during the rehabilitation. Three of the patients (P8, P9, and P10) showed no significant improvements in the maximal grip force due to the large variability among the sessions. The largest increase in grip strength was observed in patients P5 and P6 who showed continuous improvements during the entire period.

The results of the ramp task (Figure 5, below) show the average tracking errors at the beginning and at the end of training for each patient. Eight patients significantly improved their performance while reducing the tracking error. The lower tracking error suggests improved grip force control. The largest reduction in the tracking error was found in the patients P5, P7 and P9. The patients P8 and P10 showed no significant improvements in the performance of any of the training tasks.

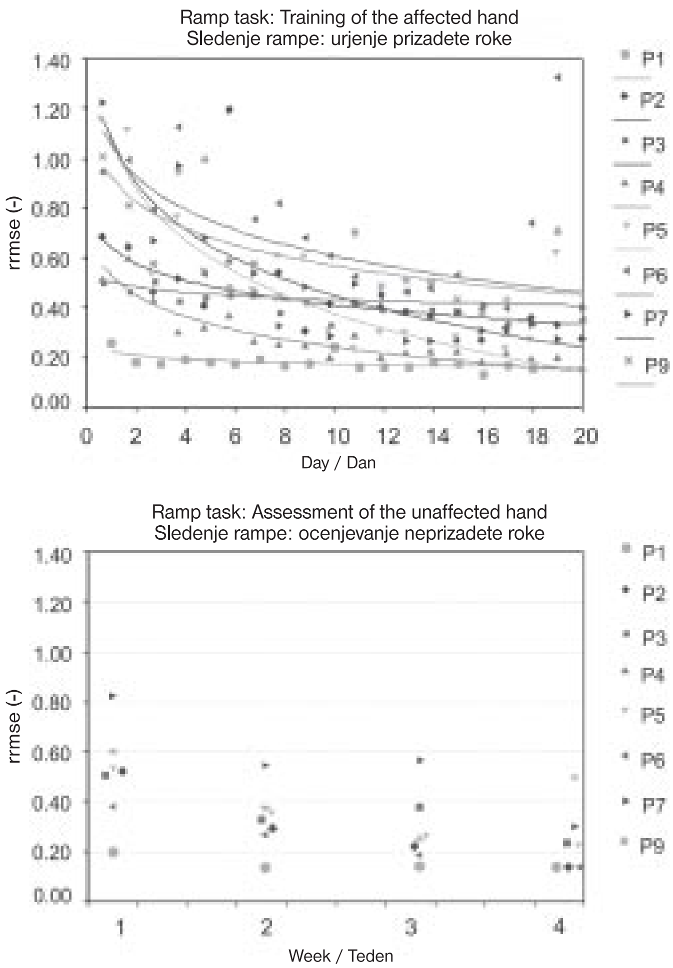

Figure 4. *The tracking results of the daily training in the ramp task showed significant reduction of the tracking error in the affected hand (above) to the performance score that was assessed in the unaffected hand (below). Logarithmic regression curves were used to evaluate the average performance trends based on the daily measurements.*

Sl. 4. *Rezultati sledenja rampe po vsakodnevnem urjenju prikazujejo opazno zmanjšanje napake sledenja s prizadeto roko (zgoraj) na vrednosti, ki so bile izmerjene pri neprizadeti roki (spodaj). Potek izboljšanja v sposobnosti upravljanja sile prijema je bil za vsakega bolnika ocenjen s prikazano logaritemsko krivuljo (zgoraj).*

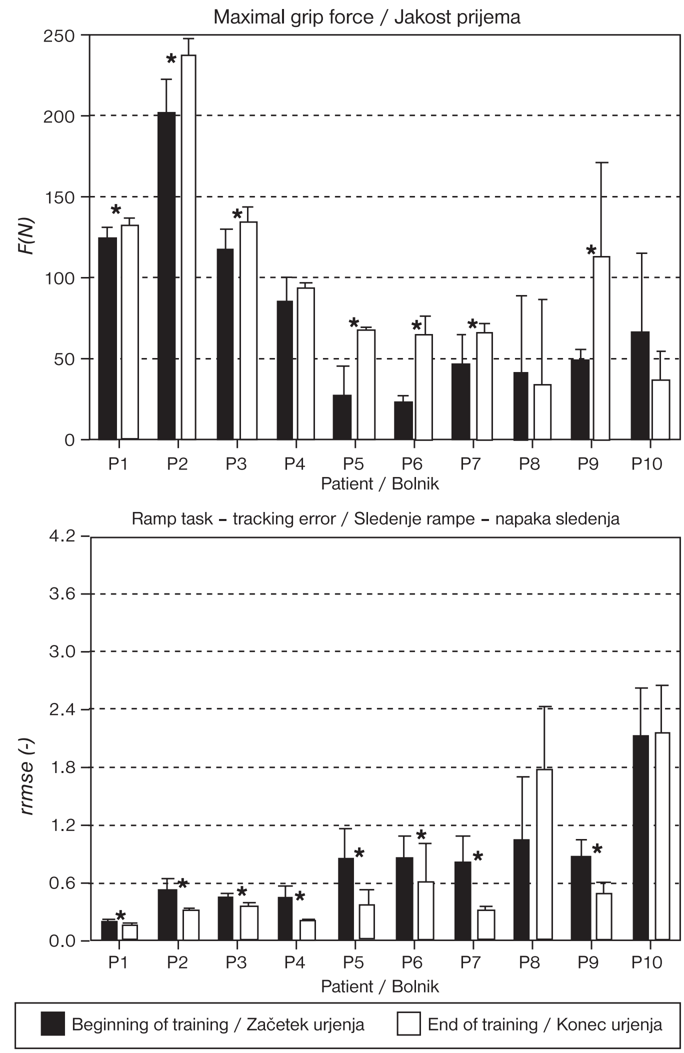

Figure 5. *The average maximal grip force (above) and the average tracking error in the ramp task (below) were obtained for the first and the last five sessions to evaluate the progress of the rehabilitation. The results show significant improvements in the grip force control in 8 out of 10 patients. (* $P < 0.05$, paired-samples t-test).*

Sl. 5. *Rezultati maksimalne sile prijema (zgoraj) ter napake pri sledenju rampe (spodaj) prikazujejo povprečje prvih petih ter zadnjih petih dni urjenja. Statistično pomembno izboljšanje v upravljanju sile je opazno pri 8 od 10 bolnikov (* P < 0,05, t-test razlike med deležema).*

Discussion and conclusions

The results of our study show improvements of the grip force control in 8 out of 10 patients after the four weeks of therapy. The difficulty of the tracking tasks was increased by raising the maximal level of the target force for each task if the patient's grip strength was increasing during the rehabilitation program. Seven patients demonstrated improvements in the maximal grip strength and the grip force control between the first and the last week of training. The reduction of the tracking error was most evident in the first few sessions. In some patients the tracking error fluctuated during the first two weeks and then the variability was reduced in the second portion of the training period. Most of the patients reduced the tracking error of their affected side to the performance that was assessed in their unaffected side. In some patients small reduction of tracking error was visible also in the unaffected side which was not trained on a daily basis, suggesting that the patient's overall sensory functions (i. e. visual and proprioceptive perception) improved during the rehabilitation. To reduce the effect of learning, randomized target signals were used instead of periodic signals. Two of the patients (P8 and P10) showed no consistent changes in the performances in any of the tasks. Their maximal grip strength remained steady during the training period, while the tracking error fluctuated between sessions. The patient P8 experienced the last stroke 6 years prior to the testing and also showed no observable improvements in other methods of therapy. The patient P10 was the oldest patient in the group (age 79) which could be a possible factor for a slow progress during the overall rehabilitation. The results indicate that the biggest improvement was visible in patients (P5, P7, and P9) who had a greatly reduced control of grasping at the start of the training.

The analysis of the force time curves showed that the highest reduction of the tracking error occurred in the sinus task which was described as the most difficult task by most of the patients. In this task the patients improved the overall accuracy of tracking and consequently achieved better grip force control. In the ramp task the patients improved the accuracy and the stability of the output force while reducing the tremor. The ramp task was therefore used also to assess the progress of the training. In the step task the patients mainly reduced overshooting of the target during the abrupt changes between the force levels. In some patients the release of the grip when changing from higher to lower levels of the target was also improved considerably. The ramp and step tasks required high activation of muscles with the aim to maximize patient's motor response. The patients who were unable to reach the 30% level of their maximal grip strength at the beginning of training improved their performance considerably and were able to reach the highest target levels in the last few training sessions.

The training with the grip force tracking system was performed in combination with regular rehabilitation program. Each training session lasted about 15 minutes per day. The individuals who participated in this study were considered to be rehabilitated to a large extent. The time from the onset of stroke until the training with tracking system was between one to six months in the patients who showed considerable improvements (Table 1). The patients were attending the occupational therapy program which was mainly focused on performing daily living activities. The patient's motor functions were evaluated by a customized functional test used at the occupational therapy department where the patients trained. The test consists of the assessment of arm movement during different functional tasks (e. g. eating, grooming), hand opening and closing, grasping and releasing of an object. Due to a non-standardized method of the assessment and the lack of validity information on the testing procedure, the results of the test are not reported in this paper.

The results of our preliminary study show that the isometric grip force training with the proposed tracking method could improve the control of grasping and the grip strength in patients after stroke. Further study in a larger and more homogenous group of stroke patients is needed to confirm the preliminary findings. Previous studies (5, 18) have shown that the cognitive information associated with the performance of the tracking task can assist the overall rehabilitation process of upper extremity function by providing feedback on the progress to the patient. The therapy with the grip force tracking system could enhance the process of relearning the sensory-motor functions after central nervous system injury. The advantage of the tracking method is also in the quantitative measure provided as a result of training which could be used to evaluate the progress of therapy. The training tasks can be automatically adjusted not to exceed patient's abilities too far. The training with the grip force tracking system was very positively accepted by the patients as well as by the therapists. The therapists reported that the patients were looking forward to daily session and they considered the training tasks as a challenge where they could continuously improve their abilities and receive immediate feedback on their performance. The proposed tracking method for training of hand function is easy to use and requires no additional preparations prior to the session. The tracking system may be used as a supplemental therapy to the standard rehabilitation exercises. Further studies are needed to evaluate the effects of the training with the tracking system in comparison to other methods of hand therapy.

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