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Grip force tracking system for assessment and rehabilitation of hand function

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Abstract. The aim of the paper is to present a novel tracking system for the assessment and training of grip force control. The system consists of two force measuring units of different shapes, which can be connected to a personal computer for visual feedback and data acquisition. We present the results of the assessment of the grip force control in 32 healthy subjects of different age groups and preliminary results obtained in a patient after head-injury who was treated with Botulinum-Toxin for hand spasticity. The proposed tracking system was also applied as a training tool in 10 post-stroke patients to possibly improve their grip force control. The results in healthy subjects showed significant differences in grip force control among different age groups. In the patient after Botulinum-Toxin treatment the method revealed noticeable effects of the therapy on the patient's tracking performance. Training with the tracking system showed considerable improvements in the grip force control in 8 out of 10 stroke patients. The proposed tracking method is aimed to be used in connection with different rehabilitation therapies (e.g. physiotherapy, functional electrical stimulation, drug treatment) to follow the influence of the therapy on patient's muscular strength and grip force control.

Keywords: Grasp, grip strength, hand, sensory motor performance, stroke rehabilitation

1. Introduction

An injury to a central nervous system, hand injury and neural or neuromuscular disease can often result in reduced hand function when performing daily activities. Different rehabilitation programmes are applied to restore patient's hand function. Objective and accurate assessment is needed to monitor and quantify patient's progress during the therapy and to validate the effects of the treatment [19]. The majority of hand function tests use qualitative or semi-quantitative measures to evaluate patient's functional state of the hand [5,11]. A number of such tests lack the objectivity and accuracy to be able to detect small changes in performance [18,19], reducing in this way the ability to more specifically adjust the therapy to the current condition of the patient.

Grip strength measurements are often included in the hand function evaluation [9]. The grip strength measurements are predominantly focused on the assessment of the maximal voluntary grip force, providing information on short-duration muscle strength [19]. The maximal grip forces are rarely used in daily

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activities, which often require more precise application and control of the grip. One of the important factors affecting the hand function is the ability to control the grip strength of sub-maximal forces which are employed during grasping and manipulation of different objects [17,23]. The classical methods for grip strength assessment using mechanical dynamometers can be improved with the use of computer assisted measurements, providing more accurate and objective results [13]. Such measurements can be performed with custom-designed instrumented objects that are in shape and size similar to objects used in daily life [9,20].

An important factor in the assessment and rehabilitation is the feedback provided to the patient on the functional condition and the performance of different tests [8]. Providing such information during or after the therapy can increase the effectiveness of the rehabilitation process [21]. This is especially important in patients where the sensory-motor functions are affected [7]. The assessment of the sensory-motor functions can be efficiently performed with tracking tasks [12]. In the tracking task a person applies the force according to the visual feedback while minimising the difference between the target and the actual response. The dynamic behaviour and range of the target can be adjusted to always maximize patient's performance. Tracking tasks have been used previously to study the development of grasping in human [1], to assess the coordination of grip force in patients with Parkinson's disease [25], as a therapy for hemiplegic patients [14] and to evaluate grip force control in patients with neuromuscular diseases [16]. The tasks can be presented in a simple desktop environment [7] or in more complex virtual environments [10].

The aim of our research was to develop an assessment tool which could be used to evaluate effects of therapy or to train patient's grip force control. Previous studies [6,7,13,25] have shown the clinical importance of grip force control assessment. The proposed application consists of a compact measuring system with two force measuring units of different shapes, which can be connected to a personal computer. The system was used in connection with a tracking task to assess the grip force control in healthy subjects of different age groups and patients with neuromuscular diseases [16]. In the paper we present preliminary measurements on a patient after head injury who was treated with Botulinum-Toxin [3] to reduce hand spasticity. The aim of the study was to obtain information on the effects of the treatment on the grip force control.

The second part of our study is focused on the use of biofeedback training for restoration of grip force control in patients after stroke. In stroke patients the ability to control and scale grip forces is greatly reduced [2]. The rehabilitation of the paretic hand consists of repetitive training of the affected muscles [4] which can be further enhanced by providing biofeedback on the exercise performance to the patient [10,27]. Biofeedback training of the sensory-motor functions can initiate reorganization of central nervous system improving the outcome of the rehabilitation [2,14,21,26]. The aim of our investigation was to employ the tracking system as a training method for a group of patients after stroke and evaluate the effects of training. The training tasks were aimed to improve the accuracy of the grip force control and enhance the ability to balance and release the grip. The patients trained over the period of four weeks in combination with the standard physical therapy.

2. Materials and methods

2.1. Grip force tracking system

The system consists of two grip-measuring devices of different shapes (cylinder and thin plate) which connect to a personal computer through an interface box (Fig. 1). Each unit is based on a single point

Fig. 1. A compact assessment system with two force measuring units 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.

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 [15,16]. The shape and the size of the force measuring units are similar to the objects used in daily activities (e.g. a cup and a key), allowing in this way the assessment of functional gripping forces. The diameter of the measuring cylinder is 55 mm and the height is 140 mm. The sensor is mounted inside the split cylindrical housing made of hard aluminium (Fig. 1). The instrument allows the assessment of forces up to 300 N 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 area of the plate is 18×30 mm^2 and the thickness of the object is about 8 mm. The load cell used can measure forces up to 360 N with the accuracy of 0.1%.

The output from the two load cells is sampled through the interface box, consisting of an amplifier with supply voltage stabilizer and an 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 sampling frequency of forces can be above 1 kHz. Additionally, six analogue signals can be measured simultaneously if required by the application (e.g. acquisition of EMG signals during the grip force measurement). For our investigation the grip force measuring system was connected to a personal computer for data acquisition and to provide visual feedback to the patient (Fig. 2). The force signal was sampled with the frequency of 100 Hz and filtered in real time by the 2nd order Butterworth filter (cut-off frequency 12.5 Hz, delay 80 ms). The delay between the input and the visual feedback, mainly originating from filtering of the signal, was below 150 ms which is the minimum time interval needed for a person to process visual information [24]. The presented task required the patient to track the target on screen by applying appropriate force to the grip-measuring device (Fig. 2). The target signal was presented with a blue ring moving vertically in the center 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. The past values of the two signals were presented as two time-varying trails (in blue and red color), which moved from the center of the screen to the left side. The aim of the task was to continuously track the position of the blue ring by dynamically adapting the grip force to the measuring unit. A graphic user interface was programmed to allow simple selection of different tracking tasks and automated data

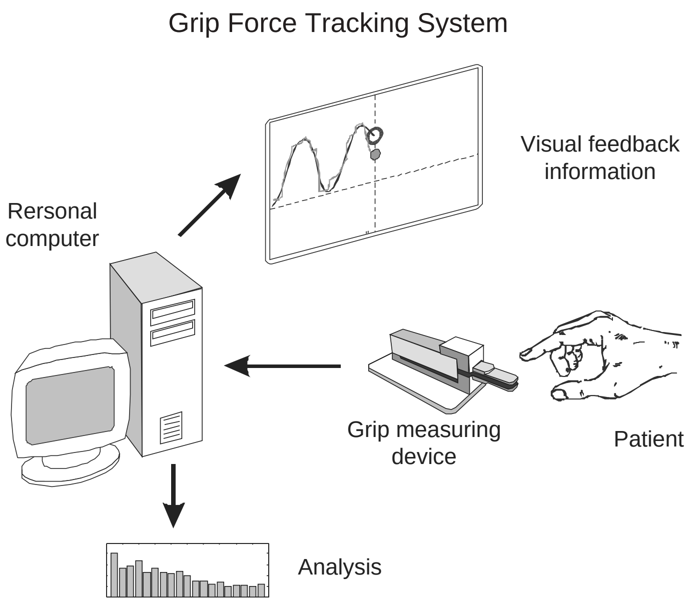

Fig. 2. Grip force control was assessed using the force tracking task where the patient applied the grip force according to the visual feedback from the computer screen.

storage. The complexity of the task was adjusted by selecting the shape of the target signal (e.g. ramp, sinus, and rectangular shape), setting the level of the target force and changing the dynamic parameters (e.g. frequency, force-rate).

2.2. *Analysis*

The patient's force tracking data are automatically stored after each task is performed to allow analysis of patient's performance at later time. The performance of the tracking is quantified by calculating relative tracking error between the target signal and the measured response [16]. The tracking error is normalized by the peak value of the target to allow the comparison of the results obtained at different force levels.

The variability of the results between groups was tested using one-way analysis of variance (ANOVA) for group samples. We considered P-values of 0.05 or less as statistically significant. The statistical analysis of the results was performed with SPSS software (Lead Technologies, Inc., Chicago, IL, USA).

2.3. *Assessment*

We investigated the grip force control in a group of 32 healthy subjects which were divided into three different age groups: 10-year old children ($n = 12$, mean age: 10 (SD 0.4) years), 25- to 35-year old adults ($n = 10$, mean age: 27.7 (SD 3.5) years) and 50- to 60-year old adults ($n = 10$, mean age: 55.6 (SD 3.1) years). The grip force control was evaluated while tracking three different targets: ramp, sinus and rectangular target. The ramp signal tracking allows quantification of the muscular strength and muscle fatigue which are particularly important in evaluation of hand function in patients with neuromuscular diseases [16]. The sinus and rectangular targets were used to evaluate dynamic characteristics of the grip force during periodic muscle activation.

During the test the subject was seated in front of the computer screen on a chair with adjustable height. The grip-measuring device was positioned at the edge of the table in the proximity of the subject's hand. The subject was asked to maintain about 90° flexion in the elbow and keep a neutral position of the shoulder. Each subject was first explained the three tracking tasks and performed one test trial of each task. For the assessment the subjects performed two trials with the ramp, three trials with the sinus target and two trials with the rectangular target in consecutive order. The sinus and rectangular targets had the frequency of 0.2 Hz and the peak force was set at 9 N for the children, 18 N for the young adults and 12 N for the older subjects. The peak forces were set at about 10% of the average maximal grip force in the lateral grip (about 150 N). The assessment was performed for the dominant and non-dominant hand.

The force tracking system was further used to evaluate the influence of Botulinum-Toxin treatment of spasticity on the grip force control in 38 year-old female patient. The patient suffered traumatic brain injury 8 years ago, resulting in the right-side hemiparesis. Precision grip was preserved but the patient had difficulties grasping objects due to the loss of muscle control. The patient was treated for spasticity of the wrist and finger flexor muscles with Botulinum-Toxin injection. We assessed her grip force control in the lateral grip one day before receiving the treatment and 6 and 13 weeks afterwards. In each session the patient performed three trials of the three tracking tasks (with ramp, sinus and rectangular target). The grip force control was evaluated by the average tracking error of the three trials in the sinus task. The assessment procedure was supervised by the patient's physician and the physical therapist. Written consent was obtained prior to the investigation. The study was approved by the ethics committee of Institute for Rehabilitation, Republic of Slovenia.

2.4. Training

The grip force tracking system was used as a training tool in 10 post-stroke patients (4 female, 6 male; mean age: 44.1 (SD 20.0) years). The average time between the onset of the condition and the training was about 5 months for the majority of the patients. The patients were attending regular occupational therapy program. For the training four different tracking tasks were programmed: assessment of maximal grip force, tracking of randomized ramp and rectangular signals and tracking of sinus signal with the increasing frequency. The properties of the signals were selected by the occupational therapist to maximize patient's performance during each session. Periodic signals were avoided not to reduce patient's attention span. The randomized ramp target was used to train patient's muscular control when gradually increasing or decreasing the grip force. The randomized rectangular target was mainly focused on closing and opening of the hand between different discrete force levels to enhance patient's grasp stability and hand opening. The sinus target with the increasing frequency was aimed to improve accuracy of the grip force control. The signal amplitudes included levels reaching up to 30% of the patient's maximal grip strength and the values of 0 N where the patient had to completely release the grip. The patients trained with the affected side for about 10–15 minutes daily, 4–5 times a week for four weeks. The unaffected side was tested once every five days to obtain reference results of each individual. The maximal grip force was assessed before each training session by the same device used for training. Patients either trained the grip force control in lateral grip or cylindrical grip, depending on the functional state of their affected hand. During the period of training with the grip force tracking system all patients received standard physical therapy. The training with the tracking system was supervised by the physical therapist. All the patients included in our study were informed of the procedures and gave consent to participate. The study was approved by the ethics committee of Institute for Rehabilitation, Republic of Slovenia.

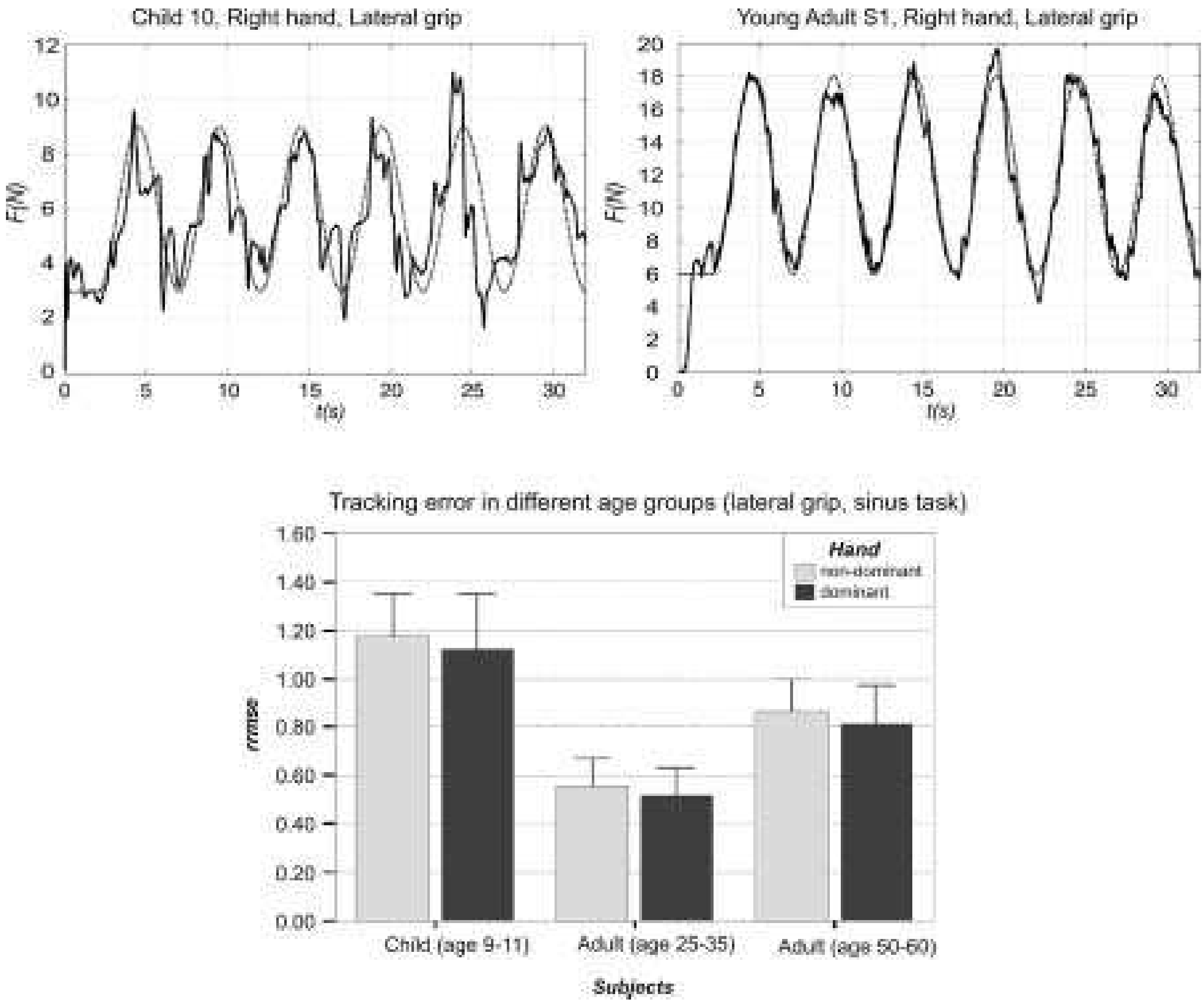

Fig. 3. Tracking results of a healthy 10-year old child and young adult (above), and the average tracking errors of three age groups of healthy subjects.

3. Results

3.1. Assessment

Figure 3 shows the results of the assessment of grip force control in three age groups of healthy subjects. Only the results of the sinus tracking are presented in the paper. The results (Fig. 3, above) show the tracking performance in a 10 year-old child and a young adult subject. The child was unable to smoothly increase and decrease the grip force which resulted in more abrupt response producing much larger tracking error (rrmse = 1.14). When the target was decreasing, the child first slightly increased the output and then decreased the grip force for a fixed force level. Results of other children show a similar approach while tracking the sinus target. The adult subject (S1) accurately tracked the target and produced a smooth response with only small deviations (rrmse = 0.48).

The performance of the tracking task was quantified by calculating the tracking error between the target signal and measured response. The bar chart in Fig. 3 (below) shows the average tracking results with standard deviation as obtained in the three age groups. The results show significant differences in the tracking accuracy among the tested groups (one-way ANOVA, non-dominant hand: $F_{2,29} = 21.268$, $p < 0.001$, dominant hand: $F_{2,29} = 13.269$, $p < 0.001$). The largest tracking error was found in the group of children, 1.173 (SD 0.282) for the non-dominant hand and 1.120 (SD 0.368) for the dominant hand. The average tracking error of the young adults was 0.552 (SD 0.165) for the non-dominant hand and 0.515 (SD 0.168) for the dominant hand. The group of older adults had the average tracking error of 0.865 (SD 0.187) for the non-dominant hand and 0.813 (SD 0.223) for the dominant hand. The lower tracking error reflects more enhanced grip force control and better hand functionality [14]. The average results of all groups show no significant influence of the hand dominancy on the grip force control.

Figure 4 shows the tracking results of a patient who suffered head injury before and after receiving Botulinum-Toxin for treatment of spasticity. Before the therapy (Fig. 4, left side), the patient was unable to gradually increase the force during the sinus tracking. The results show abrupt muscle activation patterns which resulted in non-smooth trajectory (rrmse = 1.34). The patient was overshooting the target while it was increasing. When the target force was decreasing the patient had difficulty releasing the grip which unabled her to reach the minimum peaks of the sinus. Similar pattern is also observed in the rectangular target tracking. The patient used excessive grip forces with the increasing target and was unable to regulate the output force to the desired level. The results 13 weeks after the treatment (Fig. 4, right) show that the patient was able to perform the task with much better accuracy (rrmse = 0.97). The resulting grip force trajectories are much smoother and the patient was able to increase and decrease the force within the required range. The results of the rectangular target tracking show better grip force control in patient's hand after the treatment. The patient was able to regulate the force more accurately and produced less abrupt response when the target signal was increasing. Fig. 4 (below) shows the results of the sinus tracking during the period of treatment. The results show the mean tracking error of three trials with standard deviation as obtained in each session. The patient produced considerably larger tracking errors with the affected hand as compared to the unaffected hand before receiving the treatment. After 13 weeks the patient improved her performance with the affected hand for about 30%, smaller improvements in performance were visible when the task was performed with the unaffected side. The results of the clinical tests also showed improvements in patient's hand mobility after the treatment.

3.2. Training

Figure 5 presents the result of the training with the force tracking system in 43 year-old female patient who had stroke four and a half months prior to the training. The results show patient's performance at the beginning (Fig. 5, left) and at the end (Fig. 5, right) of training for two selected tasks. Comparing the results of the rectangular target tracking shows that the patient improved the ability to control and stabilize the grip force during the constant phases of the signal. At the beginning of training the patient had difficulty keeping the grip force stable at higher force levels. After the training the accuracy of the tracking considerably improved and the output force was smoother. The results of the sinus task at the beginning of training (Fig. 5, below) show that the patient was unable to smoothly increase and decrease the grip force which resulted in more abrupt grip force response. The patient lacked the muscle capacity to track the target within the 30% of her maximal grip force resulting in large tracking error (rrmse = 1.72). After the training the patient's grip strength considerably increased and the grip force control was improved. The output of the sinus task shows a smooth response with small deviations from the target (rrmse = 0.58).

Figure 6 shows the results of the training of all patients for the maximal grip force (above) and the tracking error as assessed in the sinus task (below). The results show the average scores as obtained

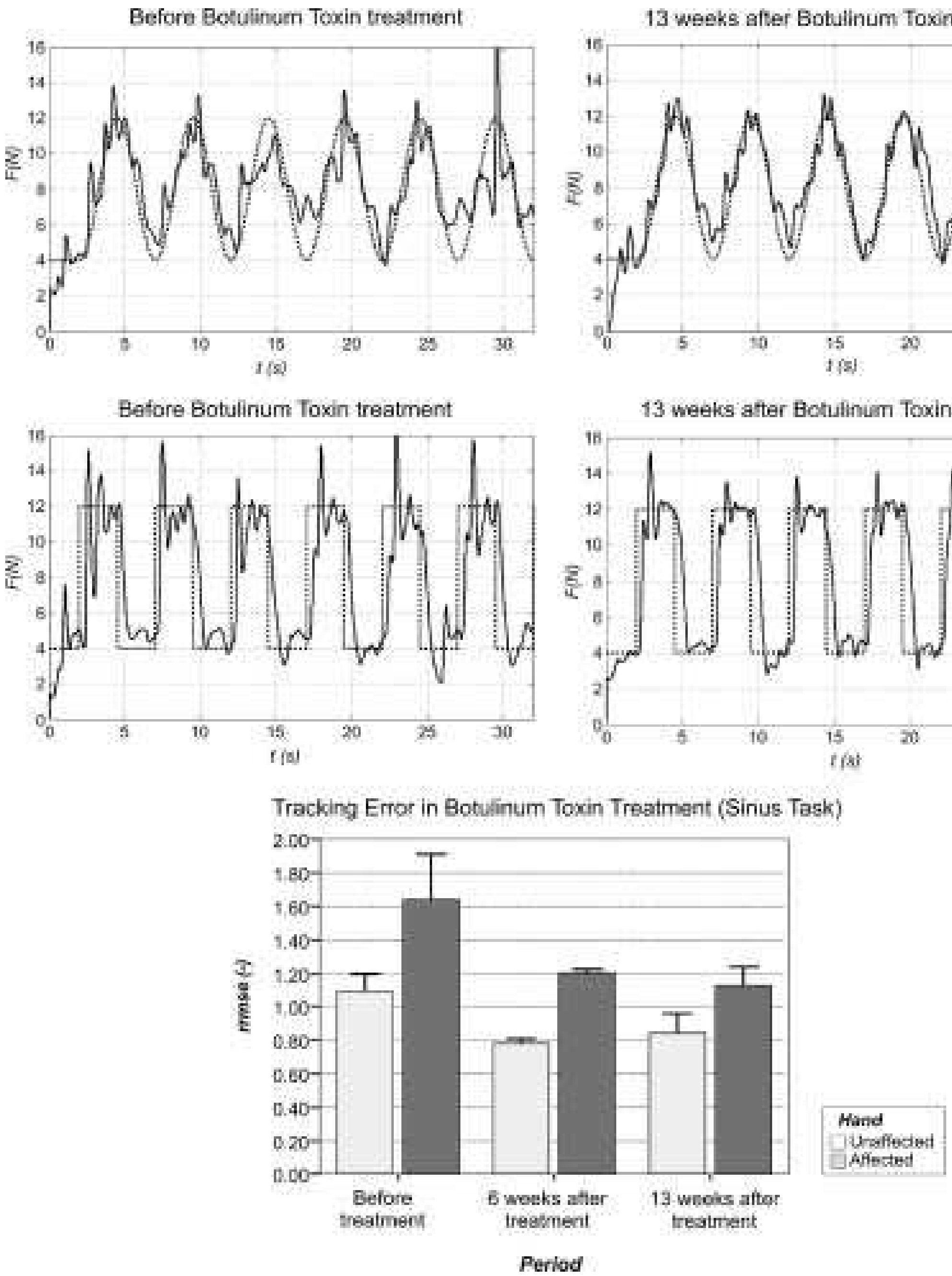

Fig. 4. Tracking results of the sinus and rectangular target tracking before and 13 weeks after the treatment with Botulinum-Toxin [5] in a patient after head injury show visible improvement of the grip force control.

during the first five and the last five training sessions. The results of the grip strength assessment show that 7 patients improved their grip strength during the rehabilitation (one-way ANOVA, $P < 0.05$). The patients P4, P8 and P10 showed no statistically significant changes in the grip strength. The percentage values in Fig. 6 indicate the amount of increase in the average maximal grip force between the first and

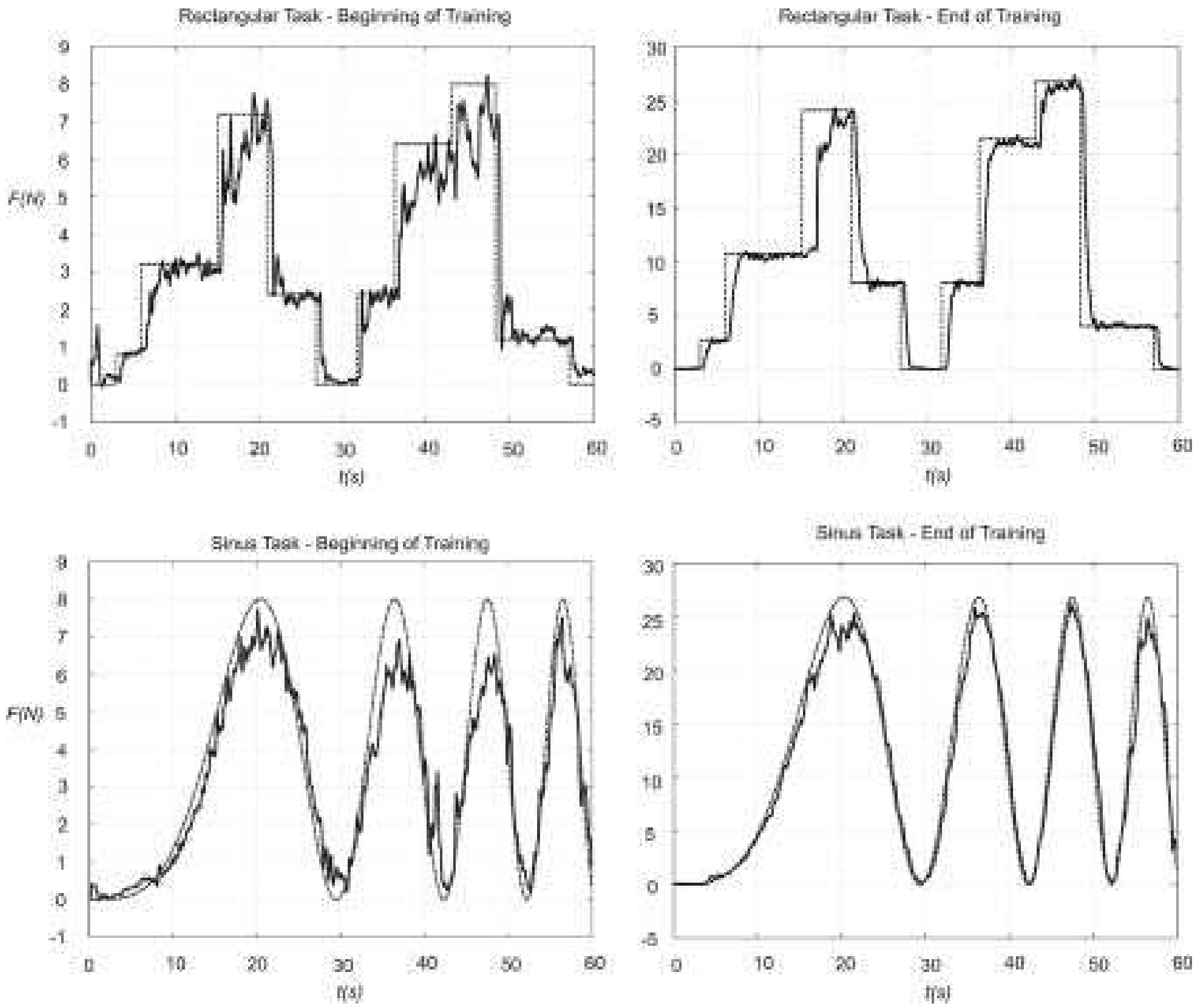

Fig. 5. The results of the tracking tasks as compared between the beginning and the end of the training period in one of the patients after stroke. The results show considerable improvements in the accuracy of the grip force control and in the release and stability of the grip after the training with the tracking system.

the last week of training. The results show large increase of the force in three patients (P5, P6, and P7) who had low grip strength at the beginning of the training. The patients who started the training with higher grip strength values demonstrated only small increase during the therapy.

The average scores of the sinus tracking task (Fig. 5, below) show that 8 patients improved their performance during the training (one-way ANOVA, $P < 0.05$). The lower tracking error suggests more enhanced grip force control [10]. The patients P8 and P10 showed no consistent results during the entire period of training. The percentage values in Fig. 6 indicate the amount of decrease of the average tracking error between the beginning and the end of training. The largest decrease of the tracking error was found in patients P5, P6, P7 and P9. The remaining patients demonstrated more advanced performance already at the beginning of training (rrmse < 1) with lesser decrease of the tracking error during the training period.

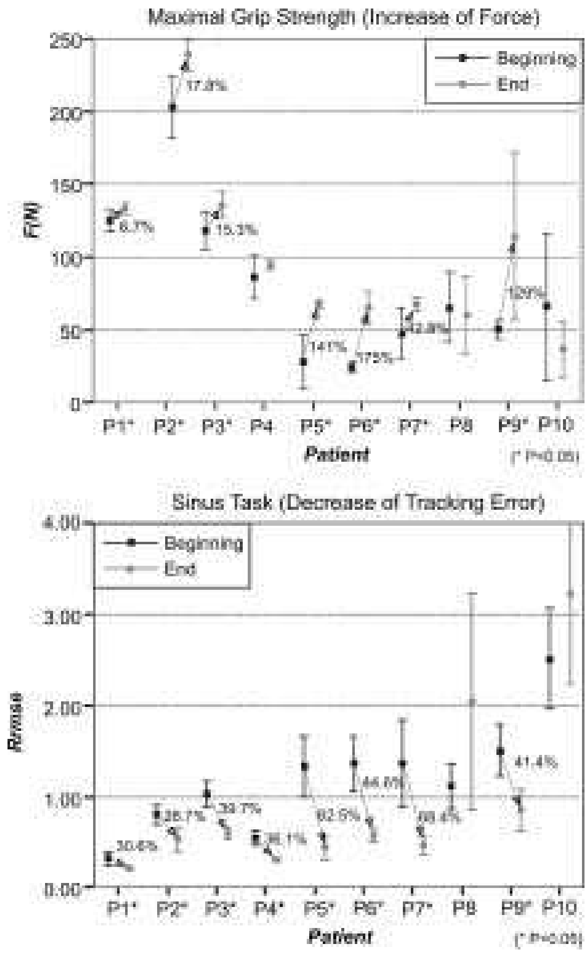

Fig. 6. The average maximal grip force and the average tracking error in the sinus task as obtained for the first and the last five sessions. The percentage values indicate the increase of the grip strength (above) and the decrease of the tracking error (below) between the beginning and the end of training. ($^*P < 0.05$, one-way ANOVA).

4. Discussion and conclusion

The aim of this paper was to present the grip force tracking system for the assessment and training of the grip force control. The system can assess the force with much greater accuracy as compared to the commonly used mechanical dynamometers and allows real-time computer assisted measurements of the applied force with the possibility to provide the patient and the therapist with visual feedback on the grip force. In this paper we presented preliminary results obtained in the healthy subjects and patients to demonstrate the use of the grip force tracking system as a method for the assessment and the training of hand function. Further studies with larger number of subjects are needed to more firmly support the findings presented.

We investigated the effect of age on the grip force control in lateral grip of 32 healthy subjects. The results show considerable differences in average tracking errors of the three age groups. The children produced more than twice as large errors as compared to the group of younger adults. The larger tracking error in children suggests that in this age group the grip force control in dynamic tasks is not yet as developed as in adults [1]. When tracking the dynamic targets, the children tend to precede the target signal and then correct the output by reducing or increasing the force. This strategy results in more abrupt force outputs. The analysis of the force-time curves of children shows similar findings as reported by Blank and colleagues [1], who assessed tracking of ramp target in 5-year old children. The 10-year old children in our study had no difficulty tracking the ramp target where the task required only gradual increase of the grip force (the results are not shown in this paper) however they adopted this strategy for the faster moving targets. We observed similar patterns in the group of older adults. The results show decrease of accuracy in the tracking when using the lateral grip. The older adults produced non-smooth trajectories with larger deviations during the decreasing phase as compared to the increasing phase. The results suggest that the grip force control is reduced with age. Future research should compare grip force control of dynamic targets under visual feedback in several age groups of children and adults to further investigate the changes of the grip force control with age and to evaluate the sensitivity of the tracking method.

Previous studies [6,14,22,26] have shown that the assessment of the force control under visual feedback using the tracking method may be useful for clinical evaluation. In the paper the preliminary results obtained in a patient after head-injury who was treated with Botulinum-Toxin for hand spasticity are presented. The results showed considerable differences in the force control between the unaffected and affected side before the treatment. The patient was unable to release the grip which resulted in reduced tracking performance in the sinus target. When increasing the force in the rectangular target tracking, the patient used excessive force and was unable to retain the required force level. The treatment with Botulinum-Toxin and the physical therapy, the patient received during this period, improved her ability to control the muscles of the affected hand. The patient was able to release and control the grip with much greater accuracy. Due to the effects of the treatment with Botulinum-Toxin [3] the patient's muscular strength decreased. The patient's hand function was clinically assessed only by means of Canadian Occupational Performance Measure (COPM) which is mainly focused on the evaluation of the functional movement tasks of the entire arm thus providing less information on hand function and the control of force. The tasks included in COPM that require accurate force control of the hand are writing and feeding tasks [17]. The patient showed improvement in writing (before: 4, after: 7) and feeding (before: 2, after: 8) with the affected hand after the therapy. Further study is needed to investigate the sensitivity of the tracking method to validate the effects of Botulinum-Toxin treatment on the grip force control and find parallels between the tracking results and the clinical tests used in occupational therapy and rehabilitation.

To investigate the effects of the isometric training of the hand function, the proposed tracking system was applied as a training method for 10 patients after stroke. Four different computer tasks were aimed to assess the maximal grip strength and to possibly improve the accuracy of the grip force control while enhancing the ability to balance and release the grip. During training the difficulty of the tracking tasks was increased by raising the maximal level of the target force to maximize patient's performance in each session. Seven patients improved their maximal grip strength and the grip force control during the training period. The analysis of the force time curves showed that the highest reduction of the error between the beginning and the end of training occurred in the sinus task which was described as the most difficult task by most of the patients. In the sinus task 8 out of 10 patients improved the overall accuracy of tracking and consequently achieved better grip force control. Two of the patients (P8 and P10) showed no consistent results of the training with their tracking scores fluctuating 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 rehabilitation. 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 patients trained with the grip force tracking system over the period of four weeks in combination with the standard physical therapy. Each training session lasted only about 15 minutes per day to minimize fatigue. The tracking tasks were very positively accepted by the patients as well as by the therapists.

The assessment of the grip force control is important for the evaluation of hand function in patients after central nervous system injury [6,14], patients affected by neuromuscular diseases [16] or Parkinson's disease [24] and persons after hand injury [6]. The proposed tracking method could be efficient in connection with different rehabilitation therapies (e.g. physiotherapy, functional electrical stimulation, drug treatment) to follow the influence of the therapy on patient's muscular strength and grip force control. The biofeedback associated with the performance of the tracking task can further assist the overall rehabilitation process by providing feedback on the progress to the patient [4,21]. The advantage of the tracking method is also in the objective measure provided as a result of training which could be used to accurately evaluate the progress of therapy. The difficulty of the tasks can be adjusted to patient's maximal abilities to advance the performance during the training. The therapy with the biofeedback on the grip force could enhance the process of relearning the sensory-motor functions after central nervous system injury as other studies suggest [14,26]. With visually more attractive feedback (e.g. in a form of a computer game) the system could be especially appropriate for training of young children and adults with sensory-motor impairments.

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