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Force tracking system for the assessment of grip force control in patients with neuromuscular diseases

Gregorij Kurillo [a,*], Anton Zupan [b], Tadej Bajd [a]

[a] Faculty of Electrical Engineering, Laboratory of Robotics and Biomedical Engineering, University of Ljubljana, Tržaška 25, 1000 Ljubljana, Slovenia
[b] Institute for Rehabilitation, Republic of Slovenia, Linhartova 51, 1000 Ljubljana, Slovenia

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Abstract

Background. The majority of hand functionality assessment methods consist of the maximal voluntary grip force measurement. Additional knowledge on sensory-motor control can be obtained by capturing functional grip force in a time frame. Tracking methods have been successfully used for the assessment of grip force control in stroke patients and patients with Parkinson's disease.

Methods. A novel tracking system for the evaluation of grip force control is presented. The system consists of a grip-measuring device with the end-objects of different shapes which was used as input to a tracking task where the patient applied the grip force according to the visual feedback. The grip force control was assessed in 20 patients with neuromuscular diseases and 9 healthy subjects. The performance of two tracking tasks was analysed in five grips. The ramp-tracking task was designed to assess the grip strength and muscle fatigue. The sinus-tracking task was used to evaluate grip force control during periodic muscle activation.

Findings. The results suggest that in some patients the disease did not affect their grip force control despite evident muscular weakness. Most patients produced larger tracking errors in precision grip while the healthy subjects showed less significant differences in performance among the grips tested.

Interpretation. The current study investigated force control in patients with neuromuscular diseases where detection of small changes in motor performance is important when following the progress of disease. The presented evaluation method can provide additional information on muscle activation and fatigue as compared to traditional grip strength testing.

Keywords: Grasp; Hand; Grip strength; Neuromuscular diseases; Sensory motor performance

1. Introduction

Grasping and manipulation of objects require an accurate grip force control to comply with the requirements of the task and properties of the object (e.g. shape, weight, friction) (MacKenzie and Iberall, 1994). Accurate grip force control is essential in performing activities such as grasping of fragile objects, resistance to external forces (e.g. holding a spoon to resist gravity), and when applying movement to the object (e.g. turning a knob) (MacKenzie and Iberall, 1994).

An injury to a central nervous system, hand injury or disease can affect neuromuscular system involved in grasping, resulting in reduced hand functionality when performing daily activities (Fugl-Meyer et al., 1975; Hermsdörfer et al., 2003). Hand functionality tests used in clinical practice (Fugl-Meyer et al., 1975; Jebsen et al., 1969) consist of picking and using different objects to accomplish selected tasks while the performance is either timed or evaluated by therapist. Computer assisted methods can greatly increase the accuracy and objectivity of the assessment while reducing the examination time and resources. The information on hand functionality is often obtained indirectly by assessing the range of motion of the fingers and wrist, grip strength and

* Corresponding author.
E-mail address: gregorij.kurillo@robo.fe.uni-lj.si (G. Kurillo).

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hand dexterity (Marx et al., 1999; McPhee, 1987). The available grip strength measurements are predominantly focused on the assessment of the maximal voluntary grip force providing information only on short-duration muscle strength (Smith, 2000). The daily activities, that involve manipulation of different objects, mostly require sub-maximal forces; therefore the assessment of the maximal voluntary grip force reflects only partial information on the hand functionality (McPhee, 1987). The grip strength is usually assessed using different mechanical dynamometers that measure the intensity of the applied grip force but no information is obtained on the dynamics and direction of the force (Innes, 1999). The dynamometers used are often not suitable for accurate measurements of low-level grip forces (typically found in patients with neuromuscular diseases) because their measurement range is too large with respect to the force applied (Innes, 1999). The measurement approach can be improved by introducing electronic dynamometers allowing real-time measurements of the grip force providing the clinician with a force–time curve (Kamimura and Ikuta, 2001). Various instrumented objects have also been proposed to assess the dynamic grip forces acting on the objects which are in shape and size similar to real objects used in daily activities (Memberg and Crago, 1997; McGorry, 2001).

In the paper we present an original grip-measuring device with differently shaped measuring objects with the aim to assess the forces in different hand postures. The grip-measuring device was used in connection with a grip-force tracking task for the evaluation of grip force control in patients with neuromuscular diseases. In the tracking task a person applied the grip force according to the visual feedback on the target signal while minimising the difference between the target and actual response. Tracking tasks have been used previously to study the sensory-motor functions (Sharp and Newell, 2000) and the development of grasping in human (Blank et al., 2000), to assess the coordination of grip force in patients with Parkinson's disease (Vaillancourt et al., 2001), as a therapy for hemiplegic patients (Kriz et al., 1995) and to evaluate the grip force control in healthy persons (Kurillo et al., 2002). The aim of our study was to present a novel method for the evaluation of the grip force control in patients with neuromuscular diseases where the quantification of the muscular weakness and hand functionality is essential to evaluate the progress of the disease (Zupan, 1996).

2. Methods

2.1. Participants

We analysed the grip force control in 20 patients with neuromuscular diseases (mean age 35.7 (SD 11.4) years), 13 of them were female and 7 were male. The control group consisted of 9 healthy male volunteers (mean age 28.4 (SD 3.4) years). All participants reported right-hand dominance. Prior to the investigation, all subjects were informed of the test procedures and gave consent to participate. The study was approved by the ethics committee of Institute of Rehabilitation, Republic of Slovenia.

2.2. Grip-measuring device

A grip-measuring device (Fig. 1) was constructed to measure the forces of different grips. The instrument developed is based on the force transducer JR3 (JR3, Inc., Woodland, USA) which can provide information on the grip strength and direction of the force (Kurillo et al., 2003). The measurement range of the sensor is 110 N in the horizontal directions and 220 N in the vertical direction. The sensor is attached to a metal construction allowing the transfer of forces from the point of contact to the sensory unit. The grip-measuring device can be fitted with different end-objects which are in shape and size similar to objects used in daily living, such as a pencil, thin plate, ball and cylinder (Fig. 1).

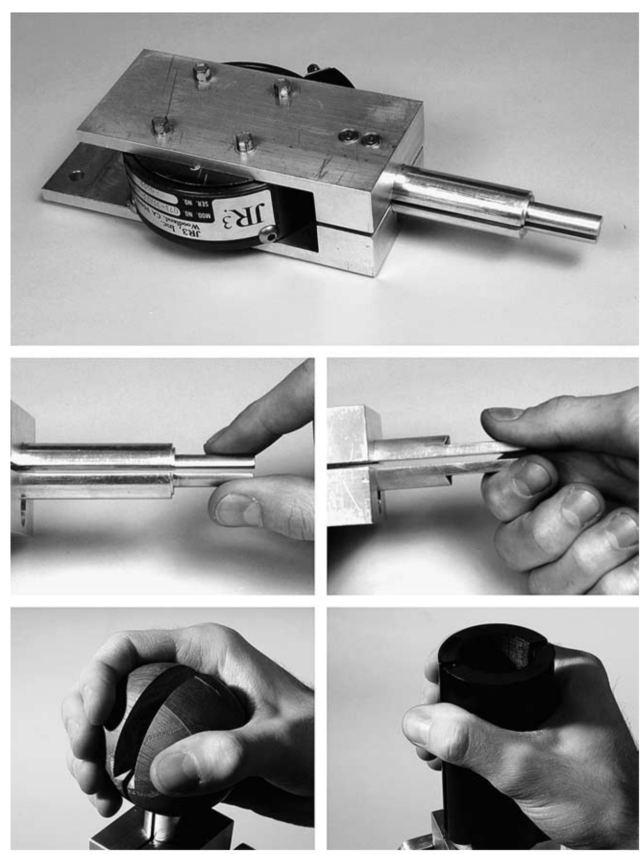

Fig. 1. A grip-measuring device with different end-objects was designed to assess forces in grips used in daily activities (e.g. nippers pinch, spherical, lateral and cylindrical grip).

Each measuring object is divided into two symmetrical halves that shape into a full object when attached to the device. The selection and the physical size of the objects were based on the Fugl-Meyer hand evaluation method (Fugl-Meyer et al., 1975). The grip-measuring device was calibrated by placing different weights at the point of contact (Kurillo et al., 2003). The device can measure forces up to 100 N with non-linearity of 1.4%. The resolution of the measured grip force is about 0.03 N.

2.3. Force tracking task

The basic scheme of the grip-force tracking system is presented in Fig. 2. The goal of the tracking task was to track the presented target as accurately as possible by applying the appropriate grip force to the end-object of the grip-measuring device. The target signal was indicated in blue colour and the force response in red colour. Vertical position of a blue ring, located in the centre of the screen, corresponded to the current value of the target and the position of a red spot corresponded to the applied grip force in real-time. The red spot moved upwards when the force was applied to the measuring object and returned to its initial position when the grip was released. The aim of the tracking task was to continuously track the position of the blue ring by dynamically adapting the grip force. The tracking task was programmed in Matlab–Simulink (The MathWorks, Inc., Natick, USA). The force applied to the grip-measuring device was sampled with the frequency of 100 Hz. The feedback signal was filtered in real-time with a 2nd order Butterworth filter (cut-off frequency 12 Hz). The complexity of the tracking task was adjusted by selecting the shape of the target signal (e.g. ramp, sinus, rectangular shape), setting the level of the required grip force and changing the dynamic parameters of the target (e.g. frequency, speed).

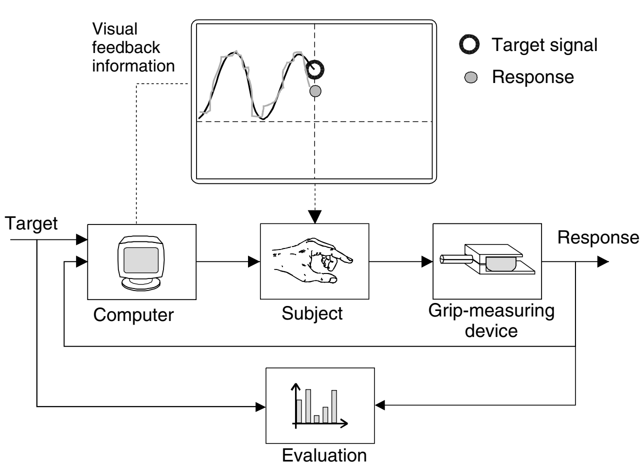

Fig. 2. The aim of the tracking task is to track the presented target as accurately as possible by applying the appropriate force to the grip-measuring device. The shape (e.g. ramp, sinus, rectangular shape), level (i.e. required grip strength) and the dynamics (e.g. frequency, speed) of the target are set individually on the computer. Evaluation of the grip force control is then performed by analysing the difference between the target and measured response.

2.4. Procedures

The tracking performance was assessed in five different grips: cylindrical, lateral, tip and nippers pinch and spherical grip, evaluating the dominant and non-dominant hand. Two different tracking tasks were selected for the evaluation of the grip force control. The first task consisted of tracking a ramp target which increased in 15 s from the initial value of 0 N to the final value of 30 N for nippers pinch, 60 N for lateral and 70 N for spherical and cylindrical grips. The peak values for each grip were selected based on our preliminary investigation involving patients with neuromuscular diseases and correspond to about 30% of the maximal voluntary grip force in healthy subjects (Mathiowetz et al., 1985). The patient was instructed to track the target as long as possible and, if unable to exert the required force, to keep the grip until the end of the trial. The trial lasted 32 s. The second task consisted of tracking a sinusoidal target with the frequency of 0.2 Hz. The amplitude of the signal was set at about 30% of the patient's maximal grip force as assessed in the ramp trial. The patient was asked to follow the moving target as accurately as possible by applying an appropriate force to the grip-measuring device.

During the test the patient was sitting in a wheelchair in front of the computer screen, with the forearm secured to a hand-support. For the maximal performance of the grip, the elbow was positioned in a 90° flexion and the shoulder was in a neutral position. The grip-measuring device was secured using a vice to prevent any movements or disturbances during testing. The patient was asked to maintain consistent grip while performing the task and was not allowed to use 'trick' movements (e.g. influencing the grip force by changing arm orientation or leaning onto the device). A therapist monitored the patient's hand posture and the test was repeated if the patient did not follow the requested procedure. The patient first performed one test trial of the tasks and then two trials of each tracking task were recorded for each grip type. The more accurate performance of the two trials was considered in further analysis. Our previous study in healthy subjects (Kurillo et al., 2002) showed low variability of the tracking results between repeated trials. The rest period between consecutive trials was 45 s. When changing grips, the person rested about 2 min. All the tasks were performed on the same day. The same procedure was followed for the control group of healthy subjects.

2.5. Data analysis

We quantified the ramp task by calculating the average maximal grip force sustained for the duration of 5s at the point where the target signal reached the maximal value (time interval 17–22 s). The results of the ramp task were used to adjust the amplitude of the sinus task aiming to suit the patient's strength abilities.

We assessed the performance of the sinus task by calculating the relative root mean square error (rrmse) between the target F_T and the measured output force F_O over the trial time T (Jones, 2000):

$$\text{rrmse} = \sqrt{\frac{1}{T}\sum_{t=2\ \text{s}}^{T=32\ \text{s}} \frac{(F_O(t) - F_T(t))^2}{\max(F_T)^2}} \quad (1)$$

The tracking error was normalised by the maximal value of the target signal to allow comparison among the results obtained in different grips and patients. A lower tracking error suggests better activation control of the corresponding muscles and improved hand functionality (Kriz et al., 1995).

The dynamic characteristics of the grip force were further assessed by analysing the coordination of tracking, which is described by the measured force $F(t)$ and calculated time derivative (i.e. force rate) $\mathrm{d}F/\mathrm{d}t$ (Jones, 2000). The trajectory obtained was plotted in the force–velocity domain, where the x-axis represented the force and the y-axis the force rate. For the sinusoidal target the normal grip force response results in a smooth circular trajectory. Producing non-smooth response during the increase or decrease of the grip force due to reduced muscle control results in deviations from the circular plot. The grip force coordination was quantified by the coefficient of coordination (K_c), defined by the correlation between the target signal and force response and the correlation of the corresponding time-rates, where the value closer to one suggests more enhanced coordination of the grip force:

$$K_c = \text{corrcoeff}(F_T, F_O) \cdot \text{corrcoeff}\left(\frac{\mathrm{d}F_T}{\mathrm{d}t}, \frac{\mathrm{d}F_O}{\mathrm{d}t}\right) \quad (2)$$

2.6. Statistical analysis

Two functional groups of patients were identified from the tracking results of the sinus task using k-means clustering algorithm (García and Gordaliza, 1999). For each group, mean tracking errors and variability of the results were analysed. One-way analysis of variance for group samples was used to compare the results among groups. We considered P-values of 0.05 or less as statistically significant. The statistical analysis was performed with SPSS software (Lead Technologies, Inc., Chicago, USA).

3. Results

3.1. Ramp task

The maximal force level reached in the ramp task was used to quantify the strength of individual patient in different functional grips when gradually increasing the force. Fig. 3 shows the results of the ramp test as performed by a healthy subject (S7) and two patients (P15 and P16) while using lateral grip of the right hand. The healthy subject was able to accurately track the ramp target without large deviations and showed no fatigue during the trial. The two patients performed the task with much larger deviations from the target signal. The patient P15 was able to track the target while increasing but was unable to retain the exerted grip force until the end of the trial. The decrease of the force was about 35% of the maximal exerted force on the interval of 15 s. The patient P16 showed large deviations when increasing the grip force. The force level reached in the lateral grip was about 45 N, representing 75% of the required level for this test. The decrease of the grip force due to muscle fatigue is evident in the results of both patients.

3.2. Sinus task

The performance of the sinus task was assessed by calculating the relative tracking error between the target and measured force (Eq. (1)). Fig. 4 shows the results of the tracking in lateral grip as obtained in the healthy subject (S7) and two patients (P15 and P16). The healthy subject accurately followed the target (rrmse = 0.45) and produced a smooth response with small deviations. Comparing the results between the two patients showed that the patient P16 had more difficulty adapting the

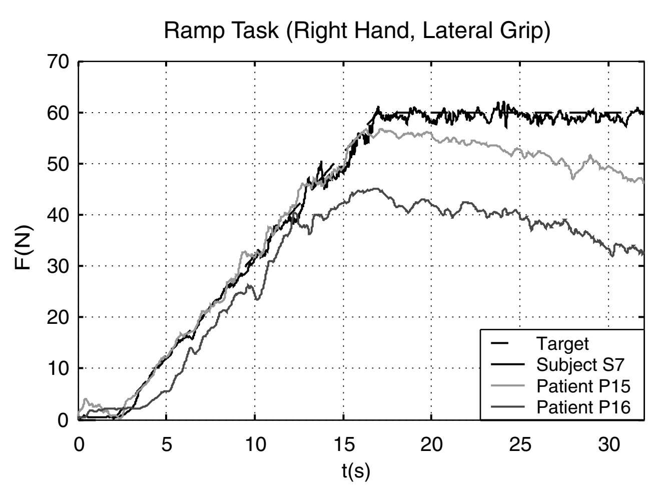

Fig. 3. The results of the ramp task as assessed in healthy subject S7 and patients P15 and P16 when using lateral grip of the right hand. The task was used to assess grip strength values for each subject.

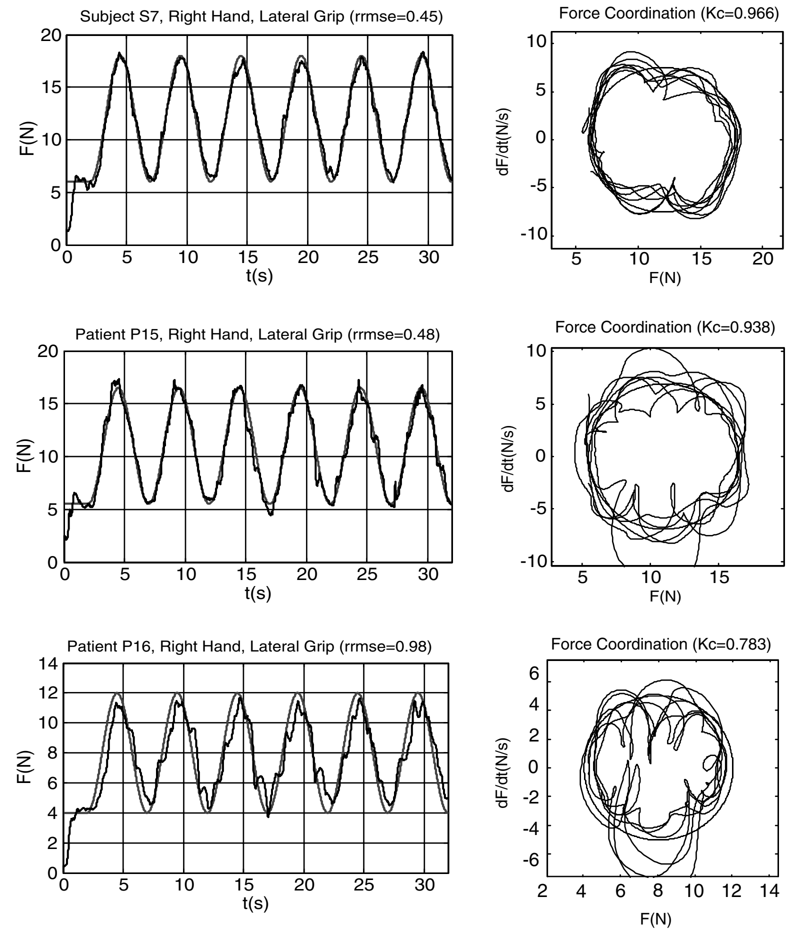

Fig. 4. The results of the sinus task as assessed in healthy subject S7 and patients P15 and P16 when using lateral grip. The measured response with respect to the target is shown on the left and the corresponding trajectory in the force–velocity space is shown on the right side.

grip force to the target and produced much higher tracking error (rrmse = 0.98) than patient P15 (rrmse = 0.48). The grip force response of the patient P16 reflects more abrupt muscle activation patterns that unable the patient to gradually increase or decrease the grip force.

The corresponding trajectory in the force–velocity domain is presented in Fig. 4 (on the right) showing the circular trajectory of the target and the trajectory of the measured grip force. The coordination of tracking was quantified by calculating the coefficient of coordination K_c (Eq. (2)). The two patients P15 ($K_c = 0.938$) and P16 ($K_c = 0.783$) produced less smooth response as compared to the healthy subject S7 ($K_c = 0.966$). The results of the patient P16 show more irregular trajectory due to abrupt changes of the grip force when tracking the sinusoidal target. Both patients used excessive force rates when increasing or decreasing the force.

The results of the tracking error varied significantly among the patients, therefore we tried to identify functional groups of patients with similar tracking performance. We analysed the tracking results of the sinus task in all grips when using the dominant and non-dominant hand. The results showed that some of the patients produced tracking errors in the range of the healthy subjects while others produced more than twice as large tracking errors. We applied k-means clustering algorithm (Garcı́a and Gordaliza, 1999) to group the patients by their grip force control. Two clusters were identified from the results of all tests and each patient was grouped based on his/her average tracking error. The first cluster was denoted as "group A", containing 11 patients with larger tracking errors and the second cluster was denoted as "group B", containing 9 patients with lower tracking errors.

In Fig. 5 the average tracking errors and the average coordination coefficients as assessed in the two groups of patients are compared to the results of the healthy subjects. The patients in group A produced on average about twice as large tracking errors (non-dominant hand: 1.10 (SD 0.25), dominant hand: 1.15 (SD 0.29)) as compared to the patients in group B (non-dominant hand: 0.64 (SD 0.14), dominant hand: 0.66 (SD 0.16)) and healthy subjects (non-dominant hand: 0.53 (SD 0.16), dominant hand: 0.52 (SD 0.17)). In both groups

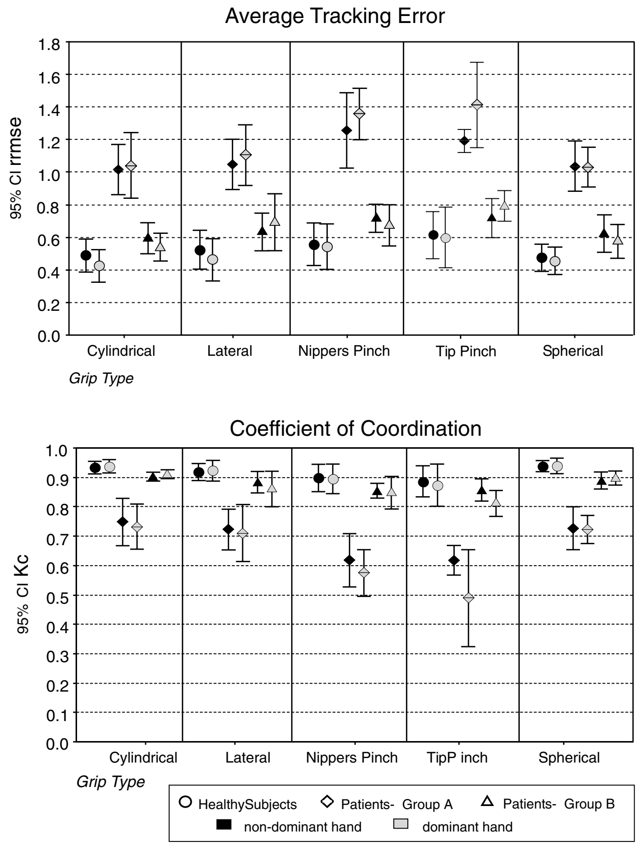

Fig. 5. The average tracking error (rrmse) and coefficient of coordination (K_c) as assessed in the healthy subjects and the two groups of patients (A and B). The charts show mean values with confidence interval (CI) of 95%.

of patients slightly larger differences in tracking error among the grips can be observed for the dominant hand. The results of both groups indicate that most patients produced larger tracking errors in nippers pinch or tip pinch as compared to the other grips (Fig. 5). Both groups of patients show significant effect of the grip type on the tracking accuracy in the dominant hand but no significant effect was found in the non-dominant hand (one-way ANOVA, non-dominant hand: $F_{4,48} = 2.221$, $P = 0.81$, dominant hand: $F_{4,48} = 4.867$, $P = 0.002$; group B: non-dominant hand: $F_{4,40} = 1.291$, $P = 0.290$, dominant hand: $F_{4,39} = 3.193$, $P = 0.023$). The tracking results of the healthy subject were not influenced by the grip type used (non-dominant hand: $F_{4,40} = 0.812$, $P = 0.525$, dominant hand: $F_{4,40} = 1.175$, $P = 0.337$). Comparing the average tracking results of the two patient groups to the healthy subjects showed significant difference in performance of the task (group A: $F_{1,194} = 334.4$, $P < 0.0001$, group B: $F_{1,177} = 28.72$, $P < 0.0001$). The tracking error results in Fig. 5 suggest that the patients from group B have more enhanced muscle control because they could perform the task in all tested grips with similar accuracy as the healthy subjects.

The analysis of the average coordination coefficient (K_c) showed significant differences between the two patient groups and the healthy subjects (group A: $F_{2,195} = 220.2$, $P < 0.0001$, group B: $F_{2,177} = 24.98$, $P < 0.0001$). The average coordination coefficient of the healthy subjects was 0.915 (SD 0.049) for the dominant hand and 0.915 (SD 0.062) for the non-dominant hand. The results of the patient group B (dominant hand: 0.869 (SD 0.066), non-dominant hand: 0.879 (SD 0.042)) reflect higher coordination of the grip force as compared to group A (dominant hand: 0.652 (SD 0.169), non-dominant hand: 0.691 (SD 0.120)). The results of patients show significant effect of the grip type on the force coordination (group A: non-dominant hand: $F_{4,48} = 3.370$, $P = 0.016$, dominant hand: $F_{4,48} = 5.930$, $P = 0.001$; group B: non-dominant hand: $F_{4,40} = 2.741$, $P = 0.042$, dominant hand: $F_{4,39} = 4.125$, $P = 0.006$). No significant effect of the grip selection was found in healthy subjects (non-dominant hand: $F_{4,40} = 2.001$, $P = 0.113$, dominant hand: $F_{4,40} = 2.130$, $P = 0.095$), which suggests that the muscle groups in healthy subjects more accurately adjust the dynamics of the exerted force while performing the tracking task.

4. Discussion

In the present study we presented a grip-force tracking system for the evaluation of the grip force control. The proposed tracking system consists of a grip-measuring device which was used to measure the grip force while grasping the objects similar to objects used in daily activities. The device 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.

Precise evaluation of hand function in the progressive neuromuscular diseases is important when following the changes in muscular weakness. The degree by which different muscles are affected by a neuromuscular disease is linked to the form of the disease and the onset of the condition. It is important to note that large differences in muscular strength and functional state can be observed also between patients with the same form of the disease. The results of clinical tests in patients with neuromuscular diseases should therefore be considered on individual basis (Zupan, 1996). In our study we examined the performance of two tracking tasks in 20 patients with neuromuscular diseases to demonstrate the use of the tracking system for the evaluation of grip force control. The ramp task allows quantification of the muscular strength and muscle fatigue which can be used to follow the progress of disease. The results of the sinus task showed that the method can provide information on muscle activation patterns during periodic muscle contraction. Comparing the results of tracking with a group of healthy subjects suggests that in some patients the disease did not affect their grip force control despite the evident muscular weakness. Most patients produced larger tracking errors in nippers pinch and tip pinch as compared to other grips. In some patients excessive force rates when increasing or decreasing the force were observed.

The tracking task presented was easy for patients to understand and even older patients with no computer experience were able to perform the task without any difficulties. The results of our previous study in healthy subjects (Kurillo et al., 2002) showed low variability of the tracking results between repeated trials, therefore only two trials were recorded for each grip. Further study could investigate the effect of training with the tracking system in the lower functional group of patients (group A) to possibly improve their grip force control. No links between the patient's performance of the tracking tasks and diagnosis were found in this study, possibly due to the small sample group and the nature of the neuromuscular diseases, where patients with the same form of the disease can be affected to a different degree (Zupan, 1996).

The proposed 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. Patient's performance can be screened before and after the applied therapy to assess its effect on the hand functionality. The cognitive information associated with the performance of the tasks can further assist the rehabilitation process by providing feedback on the rehabilitation progress to the patient. We believe that the tracking system can also be applied as a training assistive device where the difficulty of the tasks should be increased throughout the therapy promoting in this way patient's hand dexterity and grip force control.

5. Conclusions

In summary, the results of our study in patients with neuromuscular diseases showed that in some patients the disease significantly affected their grip force control in addition to the muscular weakness evident in all patients tested. Compared to healthy subjects, many patients produced much larger tracking errors in precision grips which require more accurate muscle control. Some of the patients used excessive force rates when tracking the sinusoidal target.

The presented evaluation method can provide additional information on muscle activation and fatigue as compared to traditional grip strength testing. More accurate measurements of the grip force in a time frame allow easier detection of changes in muscular strength and sensory-motor functions. Further studies in groups of patients with a particular form of neuromuscular disease are needed to obtain more information on the reduction of the grip force control during the course of the disease.

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