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Application of a Hardware and Software System of Computer Vision for Rehabilitation Training of Post-stroke Patients

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Application of a hardware and software system of computer vision for rehabilitation training of post-stroke patients allows the training procedure to be automated. It also increases the accuracy of quantitative evaluation of the results of rehabilitation and allows stage-by-stage recording of their dynamics.

Introduction

Rehabilitation training is a process of restoring higher psychic functions in patients with local brain lesions [1]. Modern programs for rehabilitation training can be differentiated into two types: conventional and automated. Conventional methods do not provide the required results because of the high cost of implementation of hardware methods of rehabilitation of neurological patients and the lack of automation of rehabilitation techniques. Besides, rehabilitation training can be performed only under in-patient conditions because of the lack of working time of neurologists.

Automated rehabilitation training is implemented in such rehabilitation systems as ARMEO (Hocoma, Switzerland), Pablo (Tyromotion, Austria), MJS 614 PLUS (BTL, Czech Republic), Neuro Move (Zynexneuro, USA), Handtutor (Israel), as well as in contactless motion capture systems, such as Virtual Rehab (Estonia), Jintronix (USA), Habilect (Russia), and Reflexion Health (USA), which are used moderately often and have a low level of automated control and medium-length preparation period.

The following statements form the methodological basis for the strategy of restorative treatment. Restoration of the system is achieved by restoring separate functions, each of which is defined as an activity directed at achieving a complete result [2]. Neuron ensembles have functional or cognitive specializations [3]. Learning is the result of formation of a new functional system (a new behavior act). During learning, new functional systems are formed by neuron selection from the reserve [4].

The goal of this work was to assess the efficiency of using a hardware and software system of computer vision for rehabilitation training of post-stroke patients.

Materials and Methods

The Visual Medicine hardware and software system of computer vision was used for rehabilitation training of post-stroke patients. The system comprises special software, computer, and video cameras (Fig. 1).

The operation of the hardware and software system is based on techniques of computer vision and machine learning. These techniques allow deriving from source images the information about hand gestures shown in these images and assessing the degree of similarity between these gestures and the reference gesture that is expected to be made by the patient at a given stage of the exercise. Both classical techniques of computer vision and machine learning (for example, contour feature analysis and support vector machines) and modern approaches (ultra-precise and fully connected neural networks) were used in constructing the algorithm. Combining computer vision and machine learning tech-

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Fig. 1. Visual Medicine system.

nologies made it possible to achieve 98% effectiveness of sample recognition.

The Visual Medicine system functionality is twofold: recording indices of speed, accuracy, and mutual coordination of motor functions (as a score) and rehabilitation training [5].

The procedure of application of the hardware and software system was automated using special software for Windows 7, 8, 10. It includes a voice assistant, gamification elements, and video recording of patient's actions during execution of the exercise. Each frame obtained using the USB camera is used as source data for the algorithm, which detects the contours of patient's hands and analyzes the reproduced gestures in real time.

The software uses computer methods of image enhancement (noise filtering, object segmentation), descriptor derivation (histograms of oriented gradients, geometric descriptors), image recognition (support vector technique [SVM], ultra-precise neural networks), and time series analysis techniques (ARIMA, etc.). Functions available from the OpenCV library are used for preliminary processing of source images from the camera and compiling the feature vector for each image. Preliminary processing is performed in the following stages: adaptive binarization (Otsu), mathematical morphology treatment, and filtering using a sliding window with a Gaussian kernel. Upon preliminary processing of the image, the contours of patient's hands are identified. Then, the image is cut along the contours of each hand and resized to 128 × 128 pixels. The gestures reproduced by each hand are recognized separately.

The following features are used to compile the descriptor vector of the cut-out image copy: geometry features describing the contour and its convex envelope and the relationship of features between them; image moments invariant to shift, rotation and scaling (Hu moments); histograms of oriented gradients (HOG). The derived features are concatenated into a single array and used as the input vector for the classifier.

Images are classified using an SVM model with a linear kernel. The model is pre-trained using synthetic data. The C language implementation of the support vector method available from the LibSVM library is used. The vector of classifier responses is an array of N numbers from the [0, 1] range with the sum equal to 1, each of which is the ascribed probability of recognition of one of the N gestures from the training sample. The series of output vectors for the series of images is analyzed to conclude on the presence or absence of given gestures in the series of images, as well as on their alteration.

The functional diagram of operation of the Visual Medicine hardware and software system of computer vision is shown in Fig. 2.

Using computer vision-based techniques for rehabilitation training makes it possible to select the order and difficulty levels of exercises with due regard to the individual characteristics and the degree of manifestation of motor disorders in post-stroke patients. Each exercise session is 10-15 min long. It includes a series of exercises

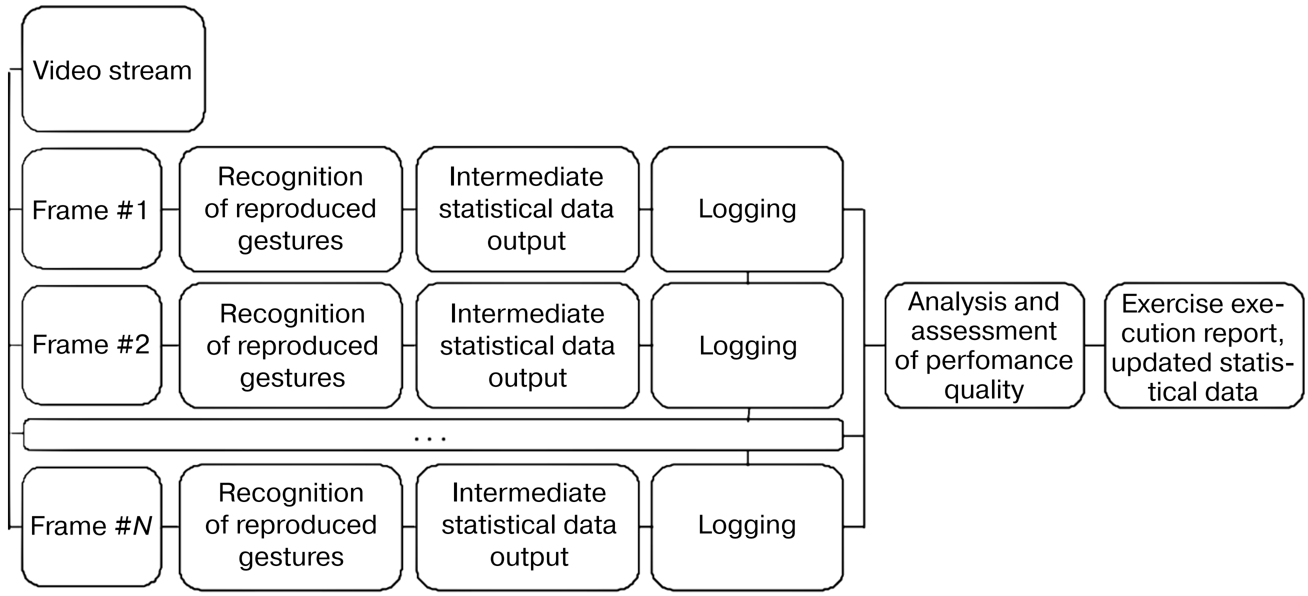

Fig. 2. Functional diagram of operation of the Visual Medicine hardware and software system of computer vision.

selected from the given set of exercises and performed in the given order. Exercises are selected individually for each patient. According to the computer vision-based procedure, the patient is given an instruction in the form of a visual sample with audio and video support. It provides the patient with the means of correcting (first, with the help of a clinical psychologist, then independently) the results of his/her performance by comparing it to the reference sample (Fig. 3).

Restorative exercises can be divided into two types: 1) repetition of a given sequence of actions for a given period of time (for example, such exercises as *Reciprocal coordination*, *Fist–border–palm*, or *Fist–border–ring*); 2) imitation of movements shown in the instructional video with audio cues.

The overall duration of the rehabilitation training program using the Visual Medicine hardware and software system of computer vision is 21 days; the running length of the program is 8 h. The program provides the possibility of automated adjustment of exercises according to the results previously achieved by the patient.

The program of rehabilitation training using the computer vision-based technique was implemented in three stages. At the first, 10-day stage, 7-8-min-long exercises were performed twice a day (during the first and second halves of the day). At the second, 5-day stage, the duration of each exercise increased to 15 min; exercises were still performed twice a day. At the third, 6-day stage, exercises were performed four times a day (twice during the first and twice during the second half of the day), while their duration was again reduced to 7-8 min.

The program was tested in 57 patients 53-61 years old undergoing restorative treatment after ischemic stroke. The patients were divided into two groups according to the stroke location: 31 patients with stroke location in the left hemisphere and 26 patients with stroke location in the right hemisphere. All patients were diagnosed with hemiparesis of various degrees of severity and mild motor aphasia. The neurological deficiency according to the Reflexion Health NIHSS scale was 6.24 ± 1.58; mean MMSE score was 25.94 ± 2.6.

The tests were performed in four stages. The rehabilitation training algorithm is illustrated in Fig. 4.

Preliminary and final tests of the lateral organization profile of the brain in post-stroke patients were performed using the Methodology of Automated Investigation of the Individual Lateral Profile. Based on the results of these tests, four patient groups were formed for participation in the main study. The first test group (T_1) comprised 19 right-handed patients with left-hemisphere stroke; the second test group (T_2), 14 left-handed patients with right-hemisphere stroke; the third test group (T_3), 12 right-handed patients with right-hemisphere stroke; the fourth test group (T_4), 12 left-handed patients with left-hemisphere stroke.

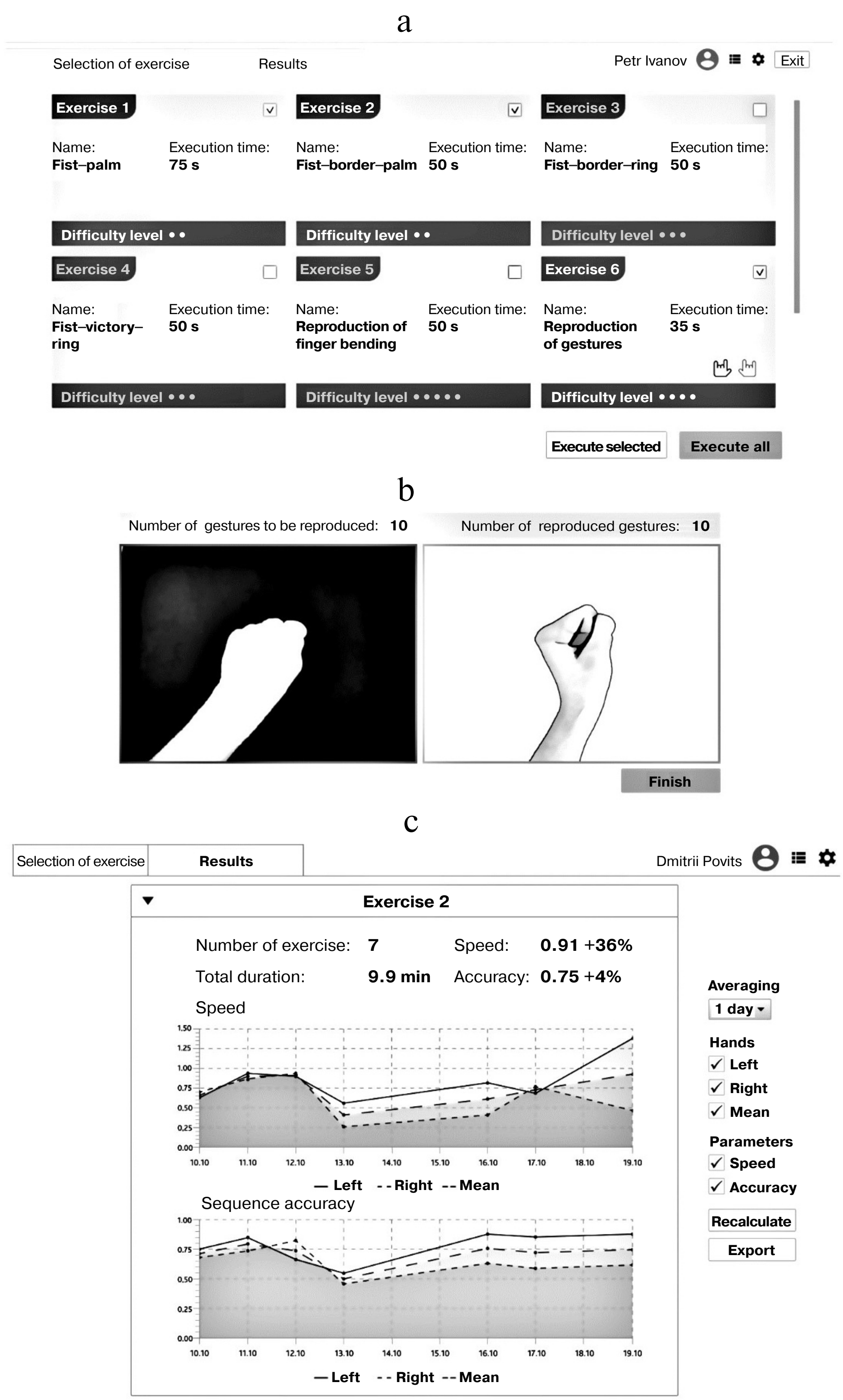

Fig. 3. Rehabilitation training software interface: a) exercise selection; b) exercise execution; c) intermediate results (execution speed and accuracy).

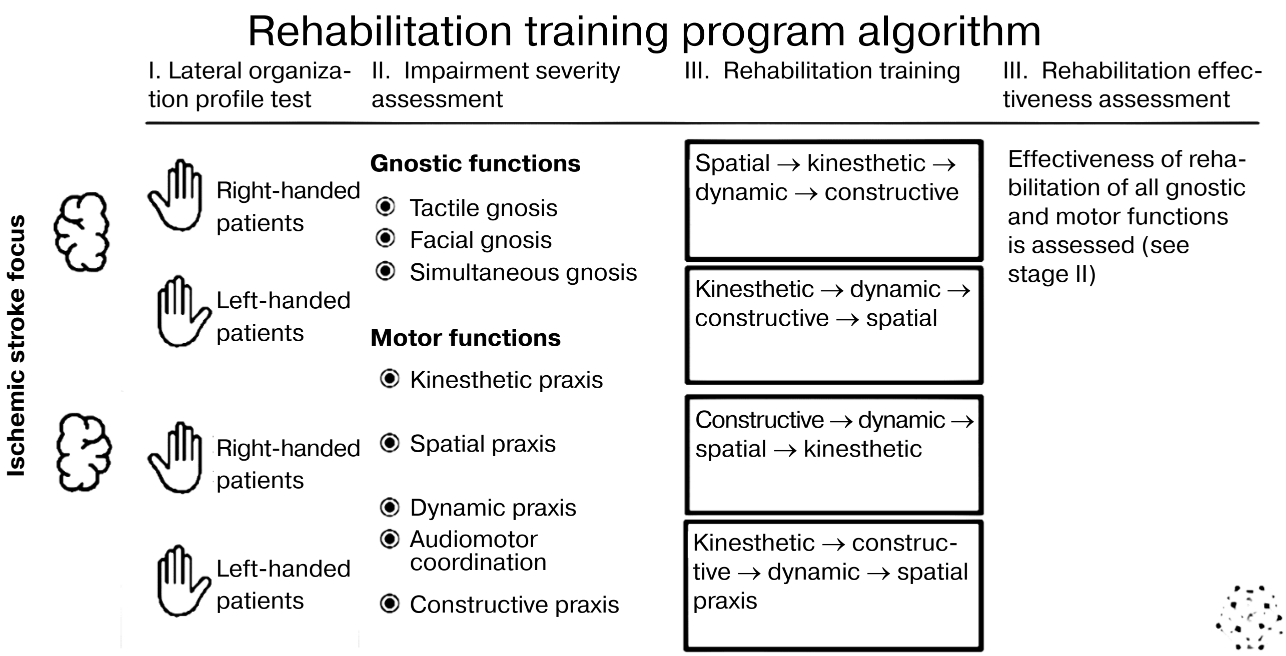

Fig. 4. Post-stroke patient rehabilitation training algorithm implemented by the hardware and software system of computer vision.

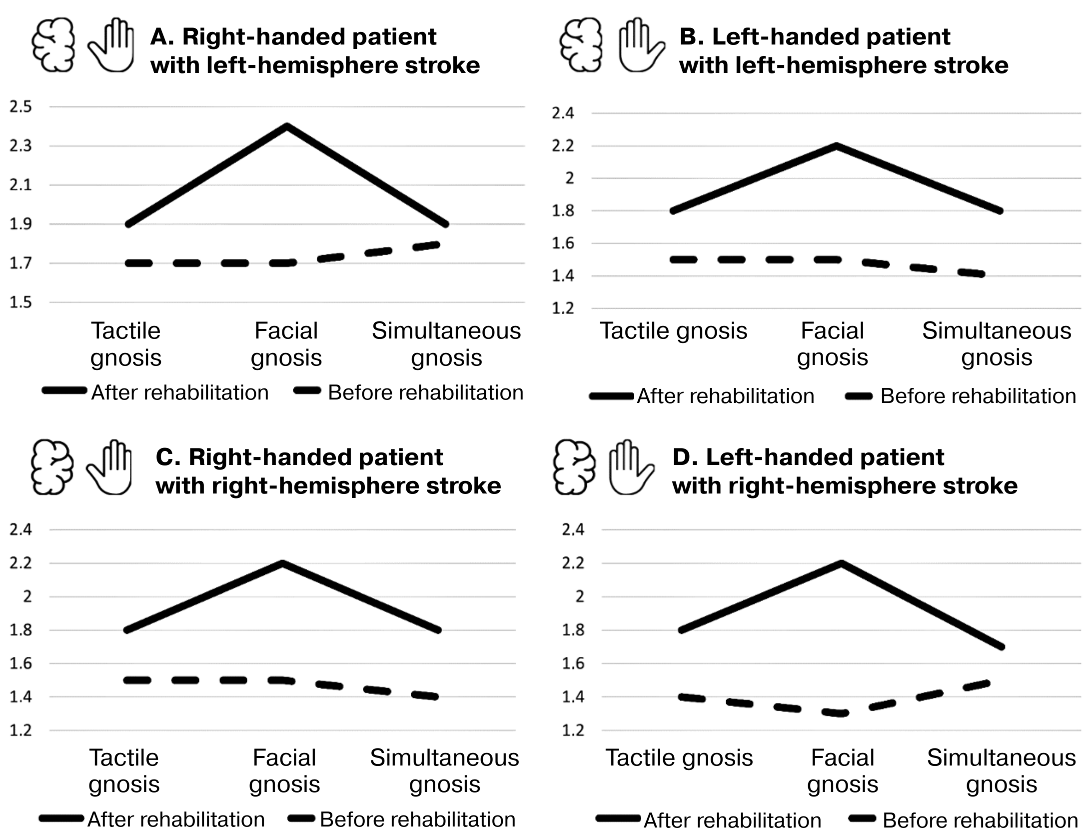

Fig. 5. Mean value profile plots of motor function disorder indices (speed) in post-stroke patients before and after rehabilitation training using the Visual Medicine hardware and software system.

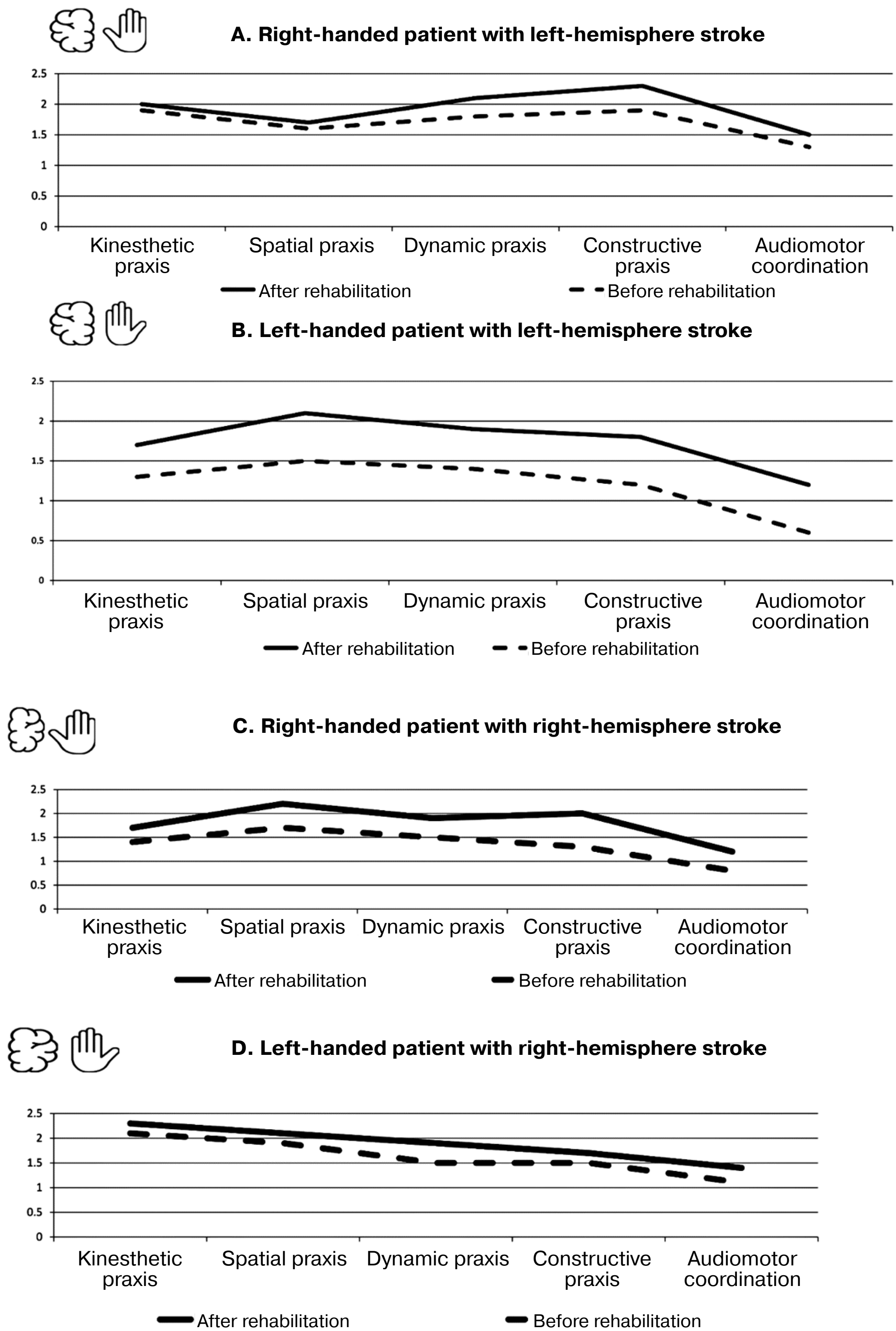

Fig. 6. Mean value profile plots of motor function disorder indices (accuracy) in post-stroke patients before and after rehabilitation training using the Visual Medicine hardware and software system.

The severity of impairment of gnostic (tactile gnosis, facial gnosis, simultaneous gnosis) and motor (kinetic praxis, kinesthetic praxis, dynamic praxis, spatial praxis, constructive praxis) functions was assessed before and after rehabilitation training using neuropsychological functional tests of speed and accuracy. The test results were expressed as a score of 0 to 3.

Results

Neuropsychological functional tests of speed and accuracy in post-stroke patients revealed more significant motor deficiency in both left- and right-handed patients with a stroke of the dominant hemisphere (Figs. 5 and 6).

The tests revealed that the rehabilitation training caused positive dynamics of motor functions in patients with left- and right-hemisphere stroke.

The recovery dynamics had some specific features depending on whether the stroke occurred in the dominant or non-dominant hemisphere. Positive dynamics was especially pronounced in left-handed patients with a stroke of the non-dominant hemisphere, while in right-handed patients with a stroke of the dominant hemisphere it was minimal.

The dynamics of effectiveness of rehabilitation training was non-uniform in all patients: during the first 11 days of rehabilitation training the effectiveness curve has a plateau (changes constitute 0.05-0.15 score); beginning with the 12th day, quantitative changes become monotonely decreasing (0.15-0.30 score).

The hardware and software system of computer vision was also shown to be effective for restoring gnostic functions (tactile gnosis, facial gnosis, simultaneous gnosis). Positive dynamics of these functions is an additional (untargeted) outcome of rehabilitation training using the system.

Discussion

Assessment of the dynamics of indices of gnostic and motor functions in post-stroke patients undergoing restorative treatment using the computer vision technique showed that the dynamics was positive in all groups of patients. Application of the computer vision-based technique of rehabilitation training in patients with an ischemic stroke of the non-dominant hemisphere led to recovery of automation of motions and actions; in patients with a stroke of the dominant hemisphere no recovery of automation of motions and actions was observed.

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