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Biomechanical Assessment of Fugl-Meyer Score: The Case of One Post Stroke Patient Who has Undergone the Rehabilitation using Hand Exoskeleton Controlled by Brain-Computer Interface

Indiko Dzhalagoniya[1*], Elena Biryukova[1,2], Yulia Bushkova[3], Marina Kurganskaia[1,2], Pavel Bobrov[1,2] and Alexander Frolov[1,2]

[1]*Institute of Higher Nervous Activity and Neurophysiology of Russian Academy of Science, Moscow, Russia*

[2]*N.I. Pirogov Russian National Research Medical University, Moscow, Russia*

[3]*Research Institute of Cerebrovascular Pathology and Stroke, N.I. Pirogov Russian National Research Medical University, Moscow, Russia*

*Corresponding author: Indiko Dzhalagoniya, Researcher, Institute of Higher Nervous Activity and Neurophysiology of Russian Academy of Sciences, 5A, ul. Butlerova, Moscow, 117485, Russia, Tel: +7-999-989-26-85; Fax: +7-499-743-00-56; E-mail: slimjeem@gmail.com

Abstract

Objective: The study is double aimed: 1) to propose a version of common protocol for an assessment of upper limb motor impairment with the use of biomechanical characteristics of Fugl-Meyer items and 2) to apply this protocol to assess an efficacy of rehabilitation using hand exoskeleton controlled by brain-computer interface during the late stage of post stroke recovery in patient with mild paresis.

Methods: One patient, 62 years old man, 10 months after ischemic stroke was recruited in the rehabilitation procedure. The patient was instructed to perform one of three tasks: to relax and to imagine kinesthetically slow extension of either paretic (left) or intact (right) hand fingers. The recorded electroencephalography was analyzed and exoskeleton extended the patient's fingers if brain-computer interface classifier recognized the imagery of their extension. The patient performed 10 daily procedures, each including three 10-minute long sessions.

14 items of Fugl-Meyer scale, describing flexor synergy (domain II), extensor synergy (domain III), movement combining synergies (domain IV) and movement out of synergy (domain V) were evaluated by standard Fugl-Meyer scores. In addition to Fugl-Meyer assessment biomechanical analysis of each item was performed. The items were recorded by electromagnetic tracking system for both paretic and intact arms. All seven degrees of freedom in each arm were taken into account. Two types of biomechanical parameters were analyzed: 1) coordination between angular velocities and 2) maximal angular velocities corresponding to seven degrees of freedom of the arm.

Results: Fugl-Meyer assessment revealed motor improvements for two items only, whereas biomechanical analysis for all 14 items considered.

Conclusion: The use of Fugl-Meyer scale completed by biomechanical parameters of its' items can be a version of common protocol for assessment of upper limb motor impairment, useful for obtaining a comparable data in different clinical studies.

Keywords: Biomechanical analysis; Fugl-Meyer score; Post stroke rehabilitation; Brain-computer interface

Introduction

Stroke is a major reason of disability worldwide. In 50-70% of cases patients get motor impairment [1], including dysfunction of upper extremity, so that it is no longer possible to perform voluntary, well-coordinated movements in everyday tasks. New rehabilitation tactics have to be introduced in order to recover lost movement coordination, muscle strength and ability to perform daily living activity. One of the promising method in post stroke rehabilitation is brain-computer interface (BCI) based on kinesthetic motor imagery which controls hand exoskeleton. Stimulation of a movement corresponding to a specific pattern of brain activity upon the detection of this pattern is an especially efficient way of reinforcing an association between an imagined movement and brain activity. Passive movement produced

by a hand exoskeleton enables the stimulation of large sensory-motor areas of the brain, further stimulating their plasticity and ultimately leading to improvement of motor control [2].

A development of new methods to estimate the efficacy of rehabilitation techniques is equally important. In all clinical controlled studies of BCI based rehabilitation [3-9] an assessment of motor function recovery was performed using standard neurological scales. Among them, Fugl-Meyer (F-M) scale [10] is most commonly used. F-M scale is valid and reliable due to a large number of items describing evolution of motor function after stroke [11-14]. Motor domains of F-M score (Table 1) are function-specific and are devoted to describe pathological synergies - flexor, extensor and combining - during the stages of post stroke recovery [15,16]. A weak point of F-M scale, like others clinical scales using discrete scores, is a subjectivity: intra- and inter-operator variability in item's assessments should always be considered a possible source of bias. More crucial is a lack of sensibility for detecting subtle changes in movement parameters. Thus, F-M scale

is most efficient in the early stages of post stroke recovery when the motor improvement is the most pronounced.

Domain	Item	Abbreviation	Relevant DoFs	Score before/after (max 2)
II Flexor Synergy	Elevation	ELEV_II	FE_s	1 / 1
	Abduction	ABD_II	ABD_s	1 / 2
	External rotation	ROTEX_II	PS_e, ROT_S	1 / 1
	Elbow flexion	EFLEX_II	FE_e	1 / 2
	Forearm supination	SUPIN_II	PS_e	1 / 1
III Extensor Synergy	Shoulder adduction/internal rotation	ADD_ROT_III	PS_e, ABD_s, ROT_s	2 / 2
	Elbow extension	EEXT_III	FE_e	2 / 2
	Forearm pronation	PRON_III	PS_e	1 / 1
IV Movement Combining Synergies	Hand to lumbar spine	HLS_III	all DoFs	1 / 1
	Shoulder flexion to 90°, elbow at 0°	SFLEX_IV	FE_s	1 / 1
	Pronation/supination of forearm with elbow at 90° and shoulder at 0°	PRON_90_IV	PS_e	1 / 1
V Movement Out of Synergy	Shoulder abduction to 90°, elbow at 0° and forearm pronated	ABDPS_V	PS_e, ABD_s	1 / 1
	Shoulder flexion from 90° to 180°, elbow at 0° and forearm in middle position	SFLEX_V	FE_s	1 / 1
	Pronation/supination of forearm, elbow at 0° and shoulder between 30° and 90° of flexion	PSE_30_V	PS_e	1/1
				17/19 (max 28)

Table 1: F-M items taking for biomechanical analysis and the scores before and after rehabilitation course.

In the late period of rehabilitation, more than 6 months after stroke, motor recovery reaches a plateau [17]. By this time, the potentials of both spontaneous recovery and traditional rehabilitation approaches are exhausted and the only rehabilitation technique stimulating the mechanisms of neuroplasticity, as BCI+exoskeleton procedure, remains to be promising. However, the late period of recovery is characterized by slow motor improvement. From 10 to 15 interventions lasting a half of hour each, which are reported in the BCI +exoskeleton studies, provide only a small changes in motor function, for which the F-M scale is not sensitive enough. It can be the reason why F-M assessment is not sufficiently convincing and, as a consequence, efficacy of BCI+exoskeleton treatment is underestimated. However, the small motor improvement can not only indicate rehabilitation efficacy, but also can be a good predictor of future motor recovery [18-20].

Sensitive instrumental method free from subjectivity, intensively used for the evaluations of post stroke motor function is biomechanical analysis of movements. Biomechanical studies of F-M items are not numerous [21-24]. High correlations were obtained between real F-M scores and biomechanical objective scores in two studies using video recordings of items of F-M domains II-V performed by 15 [21] and 41 [22] patients. Amplitude and movement smoothness were chosen for the objective scores. Another example of F-M item biomechanical analysis is the study of finger-to-nose test [23,24]. However, to our knowledge, there are no biomechanical studies of F-M items concerning a comparative analysis of movement parameters in post stroke patients before and after different kind of treatments.

In our study, the movements corresponding to the items of "flexor synergy", "extensor synergy", "combining movement synergy" and "movement out of synergy" domains of F-M scale (Table 1) were recorded and analyzed before and after BCI+exoskeleton procedure for patient with mild paresis in the late stage of post stroke recovery. Joint rotations corresponding to seven degrees of freedom (DoFs) of the arm were considered. Biomechanical parameters under analysis were 1) coordination between temporal changes of angular velocities, characterizing motor synergy and 2) maximal angular velocities, characterizing muscle torques in the joints.

Thereby the attempt is made to combine the functional advantages of F-M items with the numerical capacities of biomechanical analysis in order to reveal the potential of F-M scale and to propose a protocol sensitive enough for adequate assessment of motor function evolution resulting from post stroke rehabilitation.

Methods

Patient

One patient, 62 years old man, 10-month after ischemic stroke was recruited in the rehabilitation procedure. Following the data of magnetic resonance imaging the lesion was located in basal ganglia in the middle cerebral artery of the right hemisphere. Initial state of motor function was assessed by F-M scale as 80 points from 102 points (maximal 126 points of F-M scale minus 24 points for passive movements which have not been assessed) and by ARAT scale as 25 points (max 57). Cognitive state was assessed by MoCA scale as 24 points (max 30). The patient had an essential hypertension in third stage, diabetes of second type in subcompensation stage. The patient was able to follow instructions of rehabilitation procedure, had no other neurological, neuromuscular or orthopedic disease and no participation in any experimental intervention within the past three months.

The patient followed the BCI+exoskeleton procedure in Moscow Municipal Clinical Hospital № 31. The study protocol was conducted in accordance with the Helsinki Declaration and was approved by the Ethical Committee of the Research Center of Neurology (№12/14 of 10.12.2014). Patient provided written informed consent for participation in the study. The study protocol was registered in clinicaltrials.gov ("iMove," trial number NCT02325947).

BCI+exoskeleton procedure

During BCI+exoskeleton treatment the patient was sitting in a comfortable chair with both hands placed into the exoskeletons. The patient was instructed to perform one of three tasks following visual cues presented on the screen in front of him. The tasks were to relax and to imagine kinesthetically slow extension of either paretic (left) or intact (right) hand fingers. The recorded electroencephalographic activity was analyzed by BCI classifier described by Bobrov et al. [25]. As shown by Frolov et al. [26] this classifier only slightly loses to other more sophisticated classifiers while significantly wins in computing cost. Exoskeleton extended the patient's fingers if classifier recognized the imagery of their extension. Each daily BCI+exoskeleton procedure included three 10-minute long sessions. The patient performed 10 daily procedures. The details of the experimental setup are given in [6,7].

The percentage of correctly classified trials was used as the indicator of BCI accuracy, which depends on both the classifier performance and the participant's ability to perform motor imagery. Mean percentage of correctly classified trials during rehabilitation procedure of the patient under study was 37% that only slightly exceed the level of random recognition 33%.
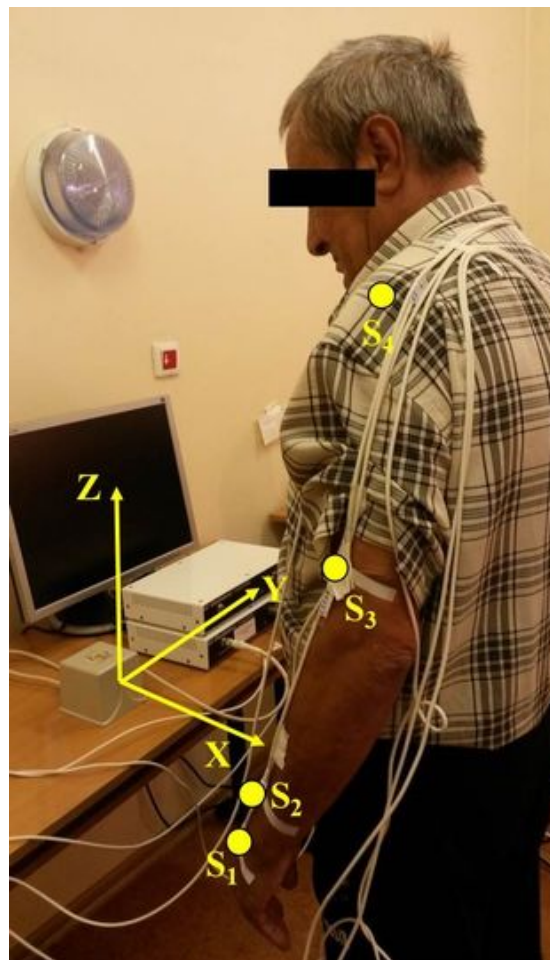
Figure 1: Experimental setup for movement registration. S_1 is the sensor on the dorsal side of the hand, S_2 is the sensor on the dorsal side of the forearm, S_3 is the sensor on the dorsal side of the upper arm, S_4 is the sensor on at the highest point of the acromion. OXYZ is the stationary system of coordinates.

Motor function assessment by Fugl-Meyer score

Scoring of each F-M item was on 3-point scale (during each F-M item execution the patient could earn maximum 2 points): 0- if the item cannot be performed at all, 1- if the item performed partly, 2-if the item performed faultlessly. In order to take into account individual motor particularities, the patient was asked first to perform each item by the intact arm. The quality of item performed by paretic arm was assessed as "performed partly" (1 point) if it did not reach the quality of item performed by the intact arm. Even when the quality of item performance increased after rehabilitation course, but did not yet reached the quality of intact arm's performance; it was still assessed by 1 point.

14 items of F-M scale, describing flexor synergy (domain II), extensor synergy (domain III), movement combining synergies (domain IV) and movement out of synergy (domain V) were taken in further biomechanical analysis (Table 1). Maximal F-M score for domains II-V was 28.

Movement registration

F-M items were registered by electromagnetic TrakStar system (Ascension Technology Corp., USA) which used the electromagnetic field to determine 3D positions and orientations (Euler angles) of the sensor systems of coordinates relative to the stationary system. Stationary system of coordinates OXYZ related with the base of TrakStar system is shown in Figure 1 by yellow axes.

Four sensors operating at a sampling rate of 200 Hz were used. The static accuracy of the TrakStar system was 0.08 cm root mean square (RMS) for the marker positions and 0.15° RMS for the marker orientations. The system was accurate within 1 m of the stationary system origin. The locations of the markers for the movement recordings were chosen to minimize their displacements relative to the arm segments. They were placed: S_1 on the dorsal surface of the hand, S_2 on the dorsal surface of the forearm, approximately 10 cm from the wrist joint, S_3 on the dorsal surface of the upper arm, approximately 15 cm above the trochlea humeri, and S_4 at the highest point of the acromion (Figure 1). The markers were attached to the skin with adhesive tape.
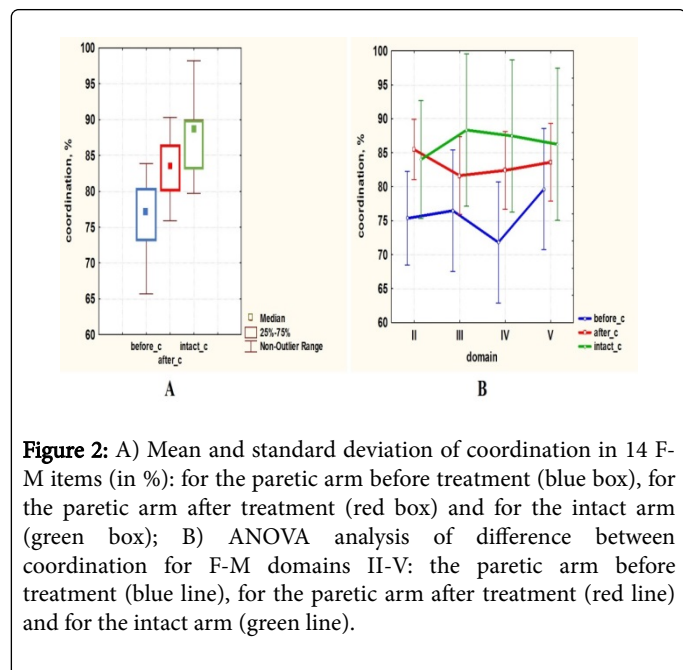
Figure 2: A) Mean and standard deviation of coordination in 14 F-M items (in %): for the paretic arm before treatment (blue box), for the paretic arm after treatment (red box) and for the intact arm (green box); B) ANOVA analysis of difference between coordination for F-M domains II-V: the paretic arm before treatment (blue line), for the paretic arm after treatment (red line) and for the intact arm (green line).

Two types of recordings were performed. First, there were the recordings of passive movements in the joints necessary for the calculation of the individual axes and centers of rotations. The patient was asked to relax and allow the physical therapist to execute sequences of three rotations following seven DoFs in the arm: three DoFs in the shoulder joint (abduction-adduction (ABD_s), flexion-extension (FE_s) and rotation about longitudinal axis of the upper arm (ROT_s)); two DoFs in the elbow joint (flexion-extension (FE_e) and pronation-supination (PS_e)) and two DoFs in the wrist joint (abduction-adduction (ABD_w) and flexion-extension (FE_w)). The rotation amplitudes were 0.7-0.8 of maximal physiological range. Special care was taken to ensure that only one of the above rotations was performed at one time.

Second, the items of F-M domains II-V enlisted in the Table 1 were recorded. All recordings were performed before and after treatment both for intact and paretic arms. F-M items for the intact arm were

assigned as the samples of individual norm [27]. Both biomechanical analysis described below and F-M assessment were based on comparison of the intact and the paretic arms movements.

Biomechanical analysis

The angular rotations following all seven DoFs of the arm-ABD_s, FE_s, ROT_s, FE_e, PS_e, ABD_w and FE_w - were calculated for each item of F-M domains II-V using the data from the sensors and the previously developed algorithms [28,29]. Angular velocities were calculated using numerical five-point scheme.
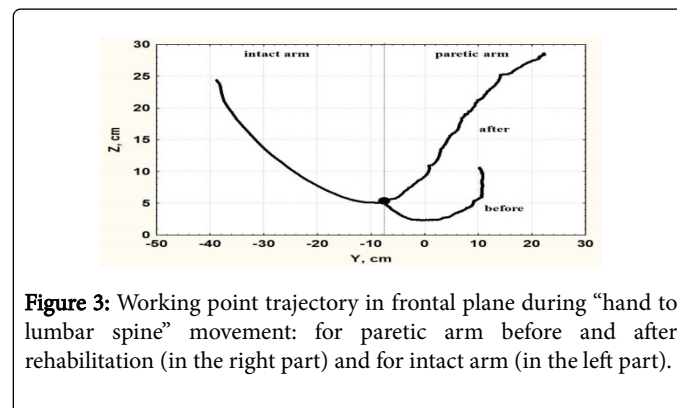
Figure 3: Working point trajectory in frontal plane during "hand to lumbar spine" movement: for paretic arm before and after rehabilitation (in the right part) and for intact arm (in the left part).

The following parameters were taken in the analysis: maximal angular velocities, considered as an index of muscle forces generating joint torque, and covariance between angular velocities (see Statistical methods), considered as an index of joint coordination during F-M items execution.

"Hand to lumbar spine" (HLS) item is the only item from domains II-V which can be considered as goal-directed movement. For this item two additional parameters were analyzed: working point (WP) trajectory defined as the trajectory of the sensor S_1 fixed to the dorsum of the hand (Figure 1) and the kinematic content of the items, i.e. temporal changes of seven joint rotations corresponding to arm DoFs.

Statistical methods

The principal component analysis was used for a compact description of the temporal changes in the seven joint rotations of the arm [30]. The covariance, not correlation of angular velocities was used in order to take into account velocity amplitudes. The choice of angular velocities, not joint angles, as the parameters of principal component analysis allows for an assessment of dynamic synergies [31,32]. The first principal component accounts for a large percentage of the total variance, this being indicative of high coordination between the joint angles. Coordination between angular velocities was measured as the percentage of total variance accounted by the first principal component.

One-way ANOVA was used for comparative analysis of F-M domains in terms of maximal angular velocities, as well as in terms of coordination between joint angles. For each item the most relevant DoFs, i.e. the DoFs contributing the most in the movement, were taken in the analysis (Table 1).

T-test was used to check statistical significance of the differences between the values of maximal angular velocities and coordination between joint angles of the intact arm and of the paretic arm before and after treatment.

Results

F-M scores

Improvement of motor function was detected for "abduction" and "elbow flexion" items of domain II. The items "shoulder adduction/internal rotation" and "elbow extension" of domain III were assessed as performed faultlessly both before and after treatment. All other items were performed partly both before and after treatment (Table 1). However, the results of biomechanical analysis presented in three next Sections evidently showed substantial improvement also in these items.

Coordination

The difference between coordination in the paretic arm joints before and after treatment was statistically significant (p=0.0009). After treatment the coordination in the paretic arm reached the level of the intact arm: the difference between them became statistically insignificant (p=0.29) (Figure 2a). ANOVA analysis showed no statistically significant differences between coordination values for different F-M domains in both intact and paretic arms neither before nor after treatment (p=0.907) (Figure 2b).

Hand to lumbar spine (HLS)

The goal of HLS test is to get the hand behind the back and to reach hand position above upper anterior superior iliac spine. HLS was assessed by F-M score as "performed partly" both before and after treatment (Table 1). However, biomechanical analysis revealed HLS significant improvement.

It is natural to consider the hand sensor S_1 (Figure 1) as WP for this movement. WP trajectories in the frontal plane are shown in Figure 3. The axis Y is directed to the right, the axis Z is directed upward (Figure 1). On the right side of vertical dotted line, the trajectories of paretic arm WP before and after treatment are shown and on the left side the trajectory of intact arm WP. All trajectories are adjusted to common initial point.

The amplitudes of WP trajectory of the paretic arm increased after rehabilitation course both for horizontal (1.5 times) and vertical (5.6 times) directions, and even exceeded the WP amplitude of the intact arm (Figure 3).
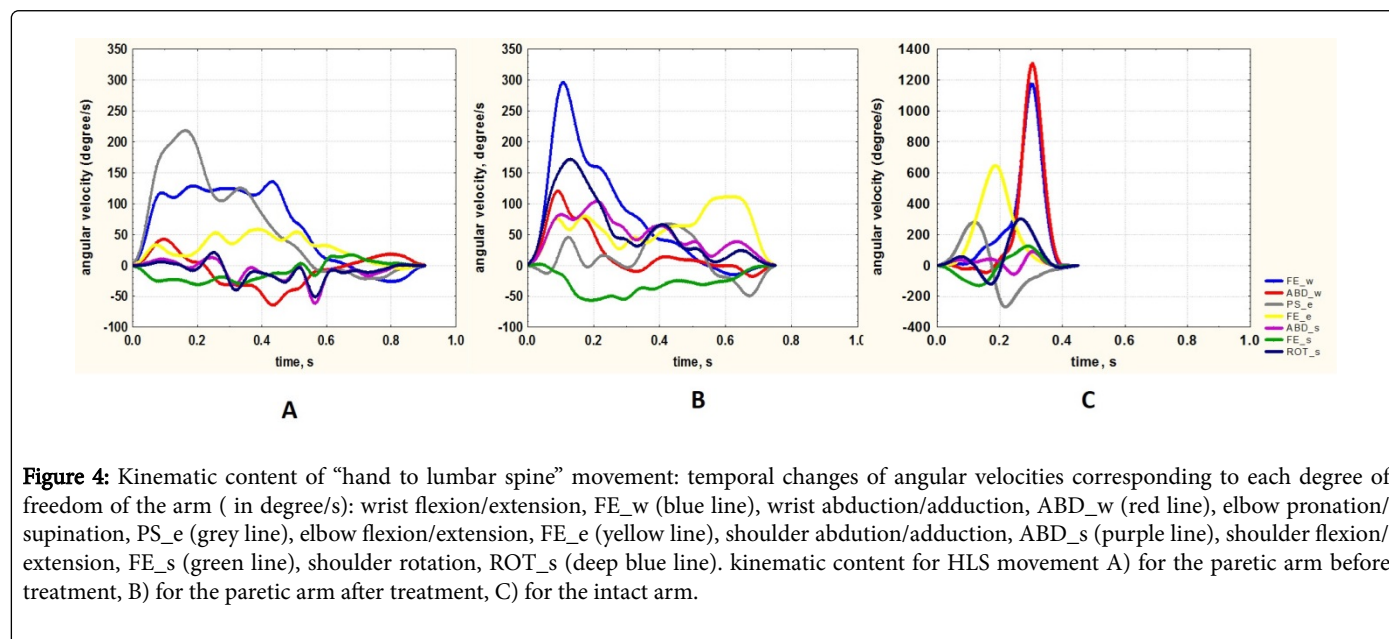
Figure 4: Kinematic content of "hand to lumbar spine" movement: temporal changes of angular velocities corresponding to each degree of freedom of the arm (in degree/s): wrist flexion/extension, FE_w (blue line), wrist abduction/adduction, ABD_w (red line), elbow pronation/supination, PS_e (grey line), elbow flexion/extension, FE_e (yellow line), shoulder abdution/adduction, ABD_s (purple line), shoulder flexion/extension, FE_s (green line), shoulder rotation, ROT_s (deep blue line). kinematic content for HLS movement A) for the paretic arm before treatment, B) for the paretic arm after treatment, C) for the intact arm.

WP amplitude increased after rehabilitation due to substantial changes in kinematic content of HLS (Figure 4). Before treatment HLS movement was implemented dominantly by distal DoFs: flexion in the wrist FE_w and pronation in the elbow PS_e (Figure 4a). After treatment proximal DoFs in the shoulder, internal rotation ROT_s and adduction ABD_s (Figure 4b), were additionally involved.

Temporal changes of joint angles of the paretic arm (Figures 4a and 4b) substantially differed from those of the intact arm (Figure 4c). In the beginning of intact arm's movement flexion in the elbow FE_e contributes the most along with twofold smaller contributions of pronation in the elbow PS_e and internal rotation in the shoulder ROT_s. During the last stage of HLS fast FE_w and ABD_w were produced. Several joint movements contributing in HLS were two-phase: PS_e included pronation followed by supination, ABD_s included adduction followed by abduction, FE_s included flexion followed by extension and ROT_s included internal rotation followed

by external one. HLS movement of the intact arm was much faster than HLS movement of the paretic arm, and much more forceful (cf. the scales on the Figures 4a-4c).

The coordination between joint angular velocities of the intact arm and of the paretic before and after treatment was only slightly different: 79.3%, 81.7% and 80.7% of total variance were taken into account by the first principal component respectively.

Maximal angular velocity

After treatment maximal angular velocity increased for the following DoFs (Figure 5). In flexion domain II: during ELEV_II for PS_e (33%), FE_e (33%) and FE_s (60%); during ABD_II for ABD_s (62%) and ROT_s (55%); during ROTEX_II for PS_e (923%); during EFLEX_II for FE_s (173%); during SUPIN_II for PS_e (124%), FE_e (42%), ABD_s (208%) and FE_s (74%). Improvement in ABD_II and

EFLEX_II was also revealed by F-M score (Table 1). As for other F-M items of domain II and for all items of domains III-V described below biomechanical analysis revealed significant differences in motor performance, while F-M score did not.

In extension domain III: during ADD_ROT_III for FE_w (147%), ABD_w (208%), FE_e (170%), ABD_s (31%), FE_s (106%) and ROT_s (75%); during EEXT_III for FE_w (81%) and FE_s (537%); during PRON_III for PS_e (52%), FE_e (86%), ABD_s (60%), FE_s (103%) and ROT_s (75%).

In the movement combining synergy domain IV: during SFLEX_IV for PS_e (60%), ABD_s (86%) and FE_s (162%); during PSE_90_IV for PS_e (94 %), ABD_s (34%), FE_s (245%) and ROT_s (150%); during HLS for ABD_w (94%), ABD_s (212%), FE_s (96%) and ROT_s (223%).

In the movement out of synergy domain V: during ABDPS_V for FE_w (174%), PS_e (641%), FE_e (32%), ABD_s (72%) and FE_s (138%); during FLEX_V for PS_e (96%), FE_e (40%) and FE_s (426%); during PSE_30_V for PS_e (35%) and FE_e (41%).

In some DoFs maximal angular velocity decreased after treatment (it is shown in Figure 5 within the dotted circle). In the flexion domain II: during ABD_II for FE_w (-64%); during ROTEX_II for ABD_s (-30%); during EFLEX_II for FE_w (-64%), ABD_w (-81%), PS_e (-31%) and ABD_s (-35%).

In the extension domain III: during EEXT_III for ABD_w (-70%) and PS_e (-41%); during PRON_III for ABD_w (-70%).

In the movement combining synergy domain IV: during SFLEX_IV for FE_w (-47%) and ABD_w (-65%); during PSE_90_IV for FE_w (-51%) and ABD_w (-50%); during HLS for PS_e (-72%).

In the movement out of synergy domain V: during FLEX_V for FE_w (-49%) and ABD_w (-36%) and ABD_s (-37%); during PSE_30_V for FE_w (-43%), ABD_w (-58%) and ABD_s (-41%).

Worth noting that the velocity increasing was much greater than the velocity decreasing: the maximal increase was 923% while the maximal decrease was 81%. Decreasing in maximal velocity concerns mostly wrist DoFs: FE_w and ABD_w (Figure 5).
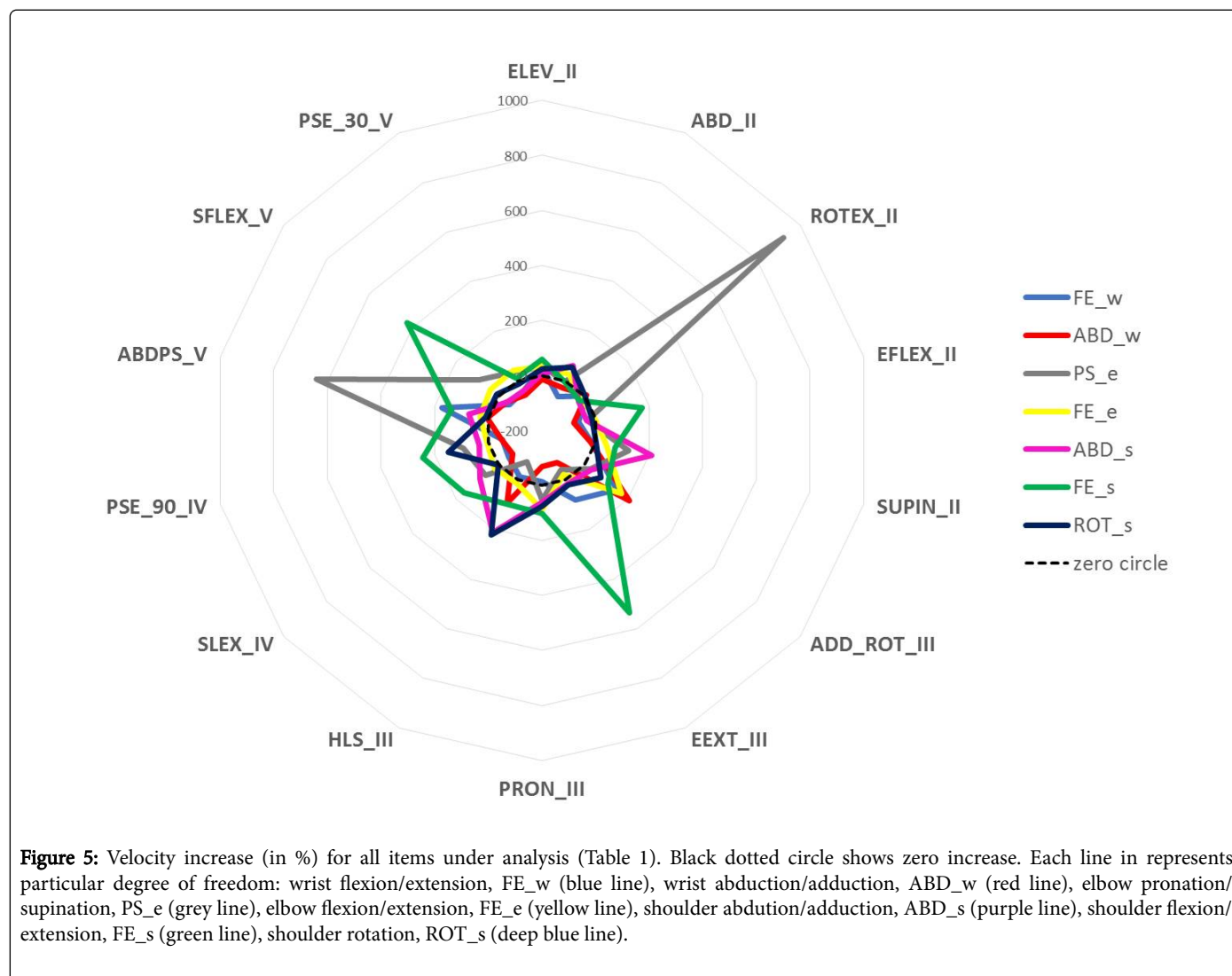

Figure 5: Velocity increase (in %) for all items under analysis (Table 1). Black dotted circle shows zero increase. Each line in represents particular degree of freedom: wrist flexion/extension, FE_w (blue line), wrist abduction/adduction, ABD_w (red line), elbow pronation/supination, PS_e (grey line), elbow flexion/extension, FE_e (yellow line), shoulder abdution/adduction, ABD_s (purple line), shoulder flexion/extension, FE_s (green line), shoulder rotation, ROT_s (deep blue line).

The difference between maximal velocity values of the paretic arm before and after treatment was statistically significant (p=0.005)

(Figure 6a). Contrary to coordination between angular velocities, the maximal velocities after treatment did not reach the level of the intact

arm: the difference between them remained statistically significant ($p<0.0001$) (Figure 6a). ANOVA analysis showed no statistically significant differences between maximal velocities values for different F-M domains in both intact and paretic arms neither before nor after treatment ($p=0.737$) (Figure 6b).
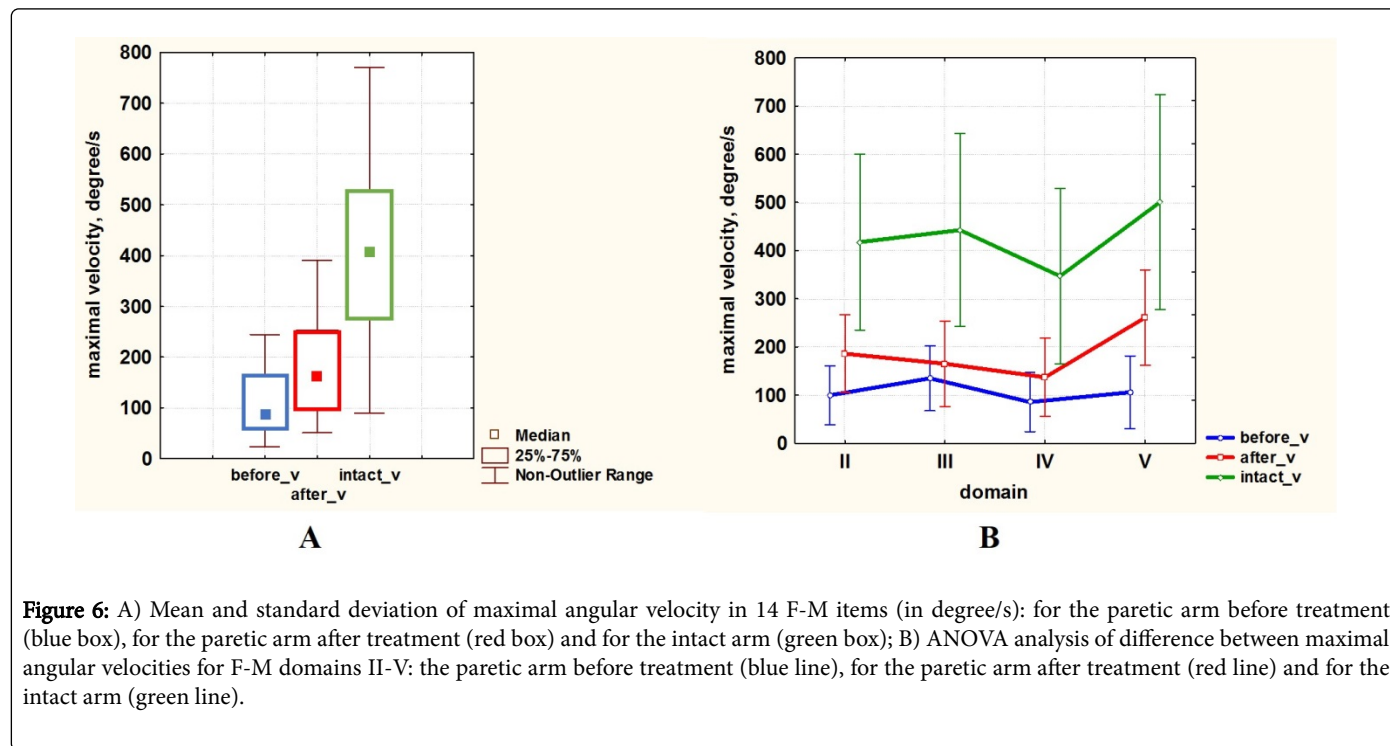
Figure 6: A) Mean and standard deviation of maximal angular velocity in 14 F-M items (in degree/s): for the paretic arm before treatment (blue box), for the paretic arm after treatment (red box) and for the intact arm (green box); B) ANOVA analysis of difference between maximal angular velocities for F-M domains II-V: the paretic arm before treatment (blue line), for the paretic arm after treatment (red line) and for the intact arm (green line).

Discussion

Our study is double aimed: 1) to propose a version of common protocol for an assessment of upper limb motor impairment on the base of biomechanical characteristics of F-M items and 2) to apply this protocol to assess an efficacy of BCI+exoskeleton treatment during the late stage of post stroke recovery. Each point discussed below will combine these two goals.

Correspondence between F-M assessments and biomechanical parameters

An improvement of motor function after BCI+exoskeleton treatment for the patient under the study was detected by F-M score only for "abduction" and "elbow flexion" items of domain II (Table 1). At the same time, biomechanical analysis revealed motor improvement in all 14 F-M items both in terms of coordination between DoFs (Figure 2) and maximal angular velocities (Figures 5 and 6).

The use of F-M score as a measurement of recovery for patients with mild motor impairment, that is the case of our study, is limited by a ceiling effect [14]. The absence of differences in F-M assessments before and after rehabilitation procedure for the majority of items (Table 1) can be related with the ceiling effect. However, substantial improvement of motor function after treatment was manifested in biomechanical parameters which are discussed below. This improvement not only demonstrates an efficacy of BCI+exoskeleton treatment, but also removes the ceiling effect of F-M scale for the case of mild paresis.

Coordination

Generally, the coordination between arm joint is studied in a small number of biomechanical studies, wherein only the coordination between elbow and shoulder flexions and trunk compensatory movements is considered [32-36]. Besides, coordination between arm joints testifies to muscle synergies which are beneficial for recognizing motor impairments in acute [37], mild, moderate [38] and chronic [39] stroke.

In contrast to movement amplitude and velocity, coordination is a parameter which assessment in the frames of F-M score is difficult. Biomechanical analysis of F-M items showed the increasing of coordination after treatment in the paretic arm joints to the level of the intact arm (Figure 2), while for the majority of items there was no differences in F-M scores. Quantitative assessment of coordination between joint movements can provide comprehensive interpretation of F-M items. In this way the coordination between flexions in the shoulder and in the elbow during finger-to-nose test, which is also the F-M item, was recently studied for patients with different levels of impairments after stroke [23,24].

The improvement of coordination is an important aspect of motor recovery, because it describes an adjusting of temporal and spatial aspects of joint rotations according to patient conditions [40]. The readjustment was revealed for HLS kinematic content which changed favorably for the increasing of WP amplitude: before treatment, distal DoFs FE_w and PS_e could not ensure sufficient WP amplitude, whereas involvement of proximal DoFs FE_e, ABD_s and ROT_s after treatment allowed for its' increasing (Figures 3 and 4). This functional DoFs readjustment is in favor of treatment efficacy. The analysis of kinematic content of F-M items, especially of goal-directed, as HLS test

or finger-to-nose test is, therefore, an effective tool of motor recovery assessment.

Maximal angular velocity

The F-M assessments "performed partly" and "performed faultlessly" refers rather to the movement amplitude, than to the movement velocity. In contrast, in biomechanical studies of post stroke movements, velocity is the most frequently used parameters, because it is a reliable index not only of muscle force, but also of muscle spasticity [41]. In addition, the velocity has been found to be more effective in discriminating mild motor impairment [36] that is the case of patient under study. Increasing of maximal velocities, corresponding to relevant DoFs was found (Figure 6a), which attests the efficacy of treatment.

There were no statistically significant differences between F-M domains II-V nor in terms of maximal velocity (Figure 6b) neither in terms of coordination (Figure 2b). It can be interpreted as a similar level of both muscle forces and coordination between DoFs in all kind of synergies described by F-M domains II-V in the patient under study.

Efficacy of BCI+exoskeleton procedure

The majority of biomechanical studies considers the difference between healthy and post stroke movements (see [41] for a review), whereas a comparative analysis of movement parameters in post stroke patients before and after different kind of treatments is much less frequently published topic [18,27,36,42,43]. For the assessment of clinical efficacy of the new method of rehabilitation, such as BCI+ exoskeleton, responsiveness of F-M scale, i.e. the sensitivity clinically meaningful change in motor function is important [44]. Following clinical experience of physical therapists and stroke neurologist's change in F-M score greater than 10% may represent a clinically meaningful improvement [14]. It was the case for the patient under study: 2 points of improvement versus initial 17 points (Table 1). Biomechanical analysis gives a numerical evaluation of physiological parameters (coordination and muscle force) for clinically meaningful improvement, and reveals subclinical changes in motor function parameters providing a prognosis of applied therapy [18-20].

Contrary to pathological gait, for which the validity of biomechanical analysis is well known and its' use is consolidated, there is still no common protocol of biomechanical assessment of upper limb impairment [45]. Assessment protocols from study to study can differ dramatically in the recording system (optoelectronic, electro-magnetic), in the analysed parameters (joint angles, velocity, smoothness, etc.) and in the analysed motion (reaching target, grasping subject, activities of daily living etc.). Biomechanical analysis of the items of F-M scale unlike F-M score, commonly accepted in clinical practice, enhances F-M scale potential and allows for completing a similar regimen in different studies.

Conclusion

The use of F-M scale completed by biomechanical parameters of its items can be a version of a common protocol for assessment of upper limb motor impairment, useful for obtaining a comparable data in different clinical studies.

References

1. Paolucci S, Bragoni M, Coiro P, De Angelis D, Fusco FR, et al. (2008) Quantification of the probability of reaching mobility independence at discharge from a rehabilitation hospital in nonwalking early ischemic stroke patients: a multivariate study. Cerebrovasc Dis 26: 16-22.

2. Lotze M, Braun C, Birbaumer N, Anders S, Cohen LG (2003) Motor learning elicited by voluntary drive. Brain 126: 866-872.

3. Ang KK, Guan C, Phua KS, Wang C, Zhou L, et al. (2014) Brain-computer interface-based robotic end effector system for wrist and hand rehabilitation: results of a three-armed randomized controlled trial for chronic stroke. Front Neuroeng 7: 30.

4. Ang KK, Guan C, Chua KS, Ang BT, Kuah CW, et al. (2011) A large clinical study on the ability of stroke patients to use an EEG-based motor imagery brain computer interface. Clin EEG Neurosci 42: 253-258.

5. Ang KK, Chua KS, Phua KS, Wang C, Chin ZY, et al. (2015) A randomized controlled trial of EEG-based motor imagery brain-computer interface robotic rehabilitation for stroke. Clin EEG Neurosci 46: 310.

6. Frolov AA, Mokienko OA, Lyukmanov RKh, Biryukova EV, Kotov SV, et al. (2017) Post-stroke rehabilitation training with a motor-imagery-based brain-computer interface (BCI)-controlled hand exoskeleton: a randomized controlled multicenter trial. Front Neurosci 11: 400.

7. Frolov AA, Mokienko OA, Lyukmanov RKh, Chernikova LA, Kotov SV, et al. (2016) Preliminary results of a controlled study of BCI–exoskeleton technology efficacy in patients with poststroke arm paresis. Bull Rus State Med Univ 2: 16-23.

8. Ono T, Shindo K, Kawashima K, Ota N, Ito M, et al. (2014) Brain computer interface with somatosensory feedback improves functional recovery from severe hemiplegia due to chronic stroke. Front Neuroeng 7: 19.

9. Ramos-Murguialday A, Broetz D, Rea M, Läer L, Yilmaz Ö, et al. (2013) Brain–machine interface in chronic stroke rehabilitation: a controlled study. Ann Neurol 74: 100-108.

10. Fugl-Meyer AR, Jääskö L, Leyman I, Olsson S, Steglind S (1975) The post-stroke hemiplegic patient. Scand J Rehabil Med 7: 13-31.

11. Duncan PW, Propst M, Nelson SG (1983) Reliability of the Fugl-Meyer assessment of sensorimotor recovery following cerebrovascular accident. Phys Ther 63: 1606-1610.

12. Duncan PW, Jorgensen HS, Wade DT (2000) Outcome measures in acute stroke trials: a systematic review and some recommendations to improve practice. Stroke 31: 1429-1438.

13. Sanford J, Moreland J, Swanson LR, Stratford PW, Gowland C (1993) Reliability of the Fugl-Meyer assessment for testing motor performance in patients following stroke. Phys Ther 73: 447-454.

14. Gladstone DJ, Danells CJ, Black SE (2002) The Fugl-Meyer assessment of motor recovery after stroke: a critical review of its measurement properties. Neurorehabil Neural Repair 16: 232-240.

15. Twitchell TE (1951) The restoration of motor function following hemiplegia in man. Brain 74: 443-480.

16. Brunnstrom S (1970) Movement therapy in hemiplegia. New York: Harper & Row.

17. Duncan PW, Lai SM, Keighley J (2000) Defining post-stroke recovery: implications for design and interpretation of drug trials. Neuropharmacology 39: 835-841.

18. Biryukova EV, Pavlova OG, Kurganskaya ME, Bobrov PD, Turbina LG, et al. (2016) Recovery of the motor function of the arm with the aid of a hand exoskeleton controlled by a brain–computer interface in a patient with an extensive brain lesion. Human Physiol 42: 13-23.

19. Kondur AA, Biryukova EV, Kotov SV, Turbina LG, Frolov AA (2016) Kinematic portrait of patient as objective index of motor function state during neurorehabilitation using the hand exoskeleton controlled by brain-computer interface. Bulletin of I.P.Pavlov St-Petersbourg Med Univ 23: 28-33.

20. Kotov SV, Turbina LG, Biryukova EV, Frolov AA, Kondur AA, et al. (2017) Rehabilitation potential of post-stroke patients training for kinesthetic movement imagination: motor and cognitive aspects. Human Physiol 43: 532-541.

21. Villàn-Villàn MA, Pérez-Rodríguez R, Martin C, Sànchez-Gonzàlez P, Soriano I, et al. (2018) Objective motor assessment for personalized rehabilitation of upper extremity in brain injury patients. NeuroRehabilitation, april 2018, in press.

22. Kim WS, Cho S, Baek D, Bang H, Paik NJ (2016) Upper extremity functional evaluation by Fugl-Meyer assessment scoring using depth-sensing camera in hemiplegic stroke patients. PLoS One 11: e0158640.

23. Rodrigues MRM, Slimovitch M, Chilingaryan G, Levin MF (2017) Does the Finger-to-Nose Test measure upper limb coordination in chronic stroke? J NeuroEng Rehab 14:6.

24. Johansson GM, Grip H, Levin MF, Häger CK (2017) The added value of kinematic evaluation of the timed finger-to-nose test in persons post-stroke. J NeuroEng Rehab 14:11.

25. Bobrov PD, Korshakov AV, Roshchin V, Frolov AA (2012) Bayesian classifier for brain-computer interface based on mental representation of movements. Zh Vyssh Nerv Deiat Im I.P. Pavlova 62: 89-99.

26. Frolov AA, Husek D, Bobrov P (2011) Comparison of four classification methods for brain computer interface. Neural Network World 21: 101-192.

27. Caimmi M, Carda S, Giovanzana C, Maini ES, Sabatini AM, et al. (2008) Using kinematic analysis to evaluate constraint-induced movement therapy in chronic stroke patients. Neurorehabil. Neural Repair 22: 31-39.

28. Biryukova EV, Roby-Brami A, Frolov AA, Mokhtari M (2000) Kinematics of human arm reconstructed from Spatial Tracking System recordings. J Biomech 33: 985-995.

29. Prokopenko RA, Frolov AA, Biryukova EV, Roby-Brami A (2001) Assessment of the accuracy of a human arm model with seven degrees of freedom. J Biomech 34: 177-185.

30. Mah CD, Hulliger M, Lee RG, O'Callaghan I (1994) Quantitative analysis of human movement synergies: constructive pattern analysis of gait. J Mot Behav 26: 83-102.

31. Grinyagin IV, Biryukova EV, Maier MA (2005) Kinematic and dynamic synergies of human precision grip movement. J Neurophysiol 94: 2284-2294.

32. Micera S, Carpaneto J, Posteraro F, Cenciotti L, Popovic M, et al. (2005) Characterization of upper arm synergies during reaching tasks in able-bodied and hemiparetic subjects. Clin Biomech 20: 939-946.

33. Levin MF (1996) Interjoint coordination during pointing movements is disrupted in spastic hemiparesis. Brain 119: 281-293.

34. Cirstea MC, Levin MF (2000) Compensatory strategies for reaching in stroke. Brain 123: 940-953.

35. Cirstea MC, Mitnitski AB, Feldman AG, Levin MF (2003) Interjoint coordination dynamics during reaching in stroke. Exp Brain Res 151: 289-300.

36. Roby-Brami A, Feydy A, Combeaud M, Biryukova EV, Bussel B, et al. (2003) Motor compensation and recovery for reaching in stroke patients. Acta Neurol Scand 107: 369-381.

37. Tropea P, Monaco V, Coscia M, Posteraro F, Micera S (2013) Effects of early and intensive neurorehabilitative treatment on muscle synergies in acute post-stroke patients: a pilot study. J Neuroeng Rehab 10: 103.

38. Roh J, Rymer WZ, Beer RF (2015) Evidence for altered upper extremity muscle synergies in chronic stroke survivors with mild and moderate impairment. Front Hum Neurosci 9: 6.

39. García-Cossio E, Broetz D, Birbaumer N, Ramos-Murguialday A (2014) Cortex integrity relevance in muscle synergies in severe chronic stroke. Front Hum Neurosci 8: 744.

40. Krasovsky T, Levin MF (2010) Toward a better understanding of coordination in healthy and poststroke gait. Neurorehab Neur Repair 24: 213-224.

41. Alt Murphy MA, Häger CK (2015) Kinematic analysis of the upper extremity after stroke how far have we reached and what have we grasped? Phys Ther Rew 20: 137-155.

42. Trombly CA (1993) Observations of improvement of reaching in five subjects with left hemiparesis. J Neurol Neurosurg Psychiatry 56: 40-45.

43. Bigoni M, Baudo S, Cimolin V, Cau N, Galli M, et al. (2016) Does kinematics add meaningful information to clinical assessment in post-stroke upper limb rehabilitation? A case report. Phys Ther Sci 28: 2408-2413.

44. Wagner JM, Rhodes JA, Patten C (2008) Reproducibility and minimal detectable change of three-dimensional kinematic analysis of reaching tasks in people with hemiparesis after stroke. Phys Ther 88: 652–663.

45. Rau G, Disselhorst-Klug C, Schmidt R (2000) Movement biomechanics goes upwards: from the leg to the arm. J Biomech 33: 1207-1216.