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Ground reaction force analysed with correlation coefficient matrix in group of stroke patients

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Stroke is the third cause of death in contemporary society and causes many disorders. Clinical scales, ground reaction force (GRF) and objective gait analysis are used for assessment of patient's rehabilitation progress during treatment.

The goal of this paper is to assess whether signal correlation coefficient matrix applied to GRF can be used for evaluation of the status of post-stroke patients.

A group of patients underwent clinical assessment and instrumented gait analysis simultaneously three times. The difference between components of patient's GRF (vertical, fore/aft, med/lat) and normal ones (reference GRF of healthy subjects) was calculated as correlation coefficient. Patients were divided into two groups ("worse" and "better") based on the clinical functional scale tests done at the beginning of rehabilitation process. The results obtained by these two groups were compared using statistical analysis.

An increase of median value of correlation coefficient is observed in all components of GRF, but only in non-paretic leg.

Analysis of GRF signal can be helpful in assessment of post-stroke patients during rehabilitation. Improvement in stroke patients was observed in non-paretic leg of the "worse" group. GRF analysis should not be the only tool for objective validation of patient's improvement, but could be used as additional source of information.

Key words: *ground reaction force, correlation coefficient, stroke*

1. Introduction

Stroke is the third chief cause of the mortality among adults in developed countries worldwide. The mortality ratio decreased up to 25% during last 30 years, independent of the clinical cause of stroke [1]. Patients who survived the stroke, and live longer than 5 years usually recover independent walking [2]. But their gait pattern is abnormal and asymmetric [3]–[5]. Patients encounter problems with balance [6], abnormal trunk and spinal motion [7]. Rehabilitation treatment is the main therapeutic approach towards functional improvement of these patients. It is very important to recognize compensatory walking patterns and establish implications for rehabilitation strategies and programs [8]. Proper rehabilitation treatment should improve patient's functional status, but it should be objectively monitored.

The aim of this paper is to assess whether analysis of ground reaction forces (GRF) using signal correlation coefficient matrix can be helpful in monitoring gait recovery in stroke patients during sub-acute phase.

2. Materials and methods

Patients

Fifty one stroke patients participated in the study (13 women and 38 men). They were aged 34 to 79 years

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old (mean = 59, SD = 10). There were 36 left side hemiplegic patients and 15 right side hemiplegic patients. Mean time from stroke incidence to the inclusion to the study was 39.6 days (SD = 17). Mean Body Mass Index was 28.0 (SD = 4.2) at the beginning of the study.

Stroke patients were admitted to the 2nd Department of Neurology, Institute of Psychiatry and Neurology in Warsaw and recruited to the present study according to the established criteria. The inclusion criteria were as follows: (1) first ischemic stroke (confirmed by Computer Tomography (CT) or Magnetic Resonance (MRI) > 1 month prior to study enrollment and not more than 3 months, (2) presence of a motor deficit in their lower extremity as assessed with Fugl–Meyer subscale for lower extremity test (3), a score of ≥ 24 on the Mini Mental Status Examination, (5) lack of neglect syndrome (clinically assessed by neuropsychologist), (6) a score ≥ 3 on the Goodglass-Kaplan Aphasia Examination, (7) self-awareness of disease, (clinically assessed by neuropsychologist) (8) ability to walk 10 meter independently without any orthotic device or help of another person, (9) constant (5 days/week) institutionalized physiotherapy during 4 weeks prior to study enrollment, and (10) signed informed consent.

The exclusion criteria were: neglect syndrome, deep dysphasia or medical contraindications to perform intensive training.

Patients underwent twelve weeks' physiotherapy program (two hours of individual motor therapy per day, and five days a week) which was aimed at gait recovery. All patients were treated for first 6 weeks in an in-patient ward, and they were treated in an out-patient clinic for the following 6 weeks.

The study was carried out for 2 years. The study was approved by the Local Ethical Committee.

Gait analysis

Patients underwent instrumented gait analysis three times: prior to the beginning of the rehabilitation program, after 6 weeks and 12 weeks of the rehabilitation program. Gait analysis was performed using six-camera VICON 460 system (60 Hz of camera frequency) with synchronized Kistler platform. After a few trials for achieving natural gait stereotype with self-selected, preferred speed, data were captured. Kinetic data averaged from session of at least 6 trials by Polygon software were exported to ascii files and analyzed with self created procedure in Matlab (Signal Toolbox). Signal correlation coefficient of each coordinate (X, Y, Z) of ground reaction force (GRF) and coordinate of normal reference [9] was calculated for all sessions for paretic and non-paretic side. Matrix of correlation coefficients (R) is related to the covariance matrix (C) and mutual relationship is established as follows

$$R(i,j) = \frac{C(i,j)}{\sqrt{C(i,i)C(j,j)}}\,. \tag{1}$$

Averaged speed for each patient and session was calculated. Then normalized speed (speed %) was calculated as percentage of patient's speed value with respect to sex and age matched against normal one. Normal data were taken from that published by Öberg et al. [10].

Clinical evaluation

All patients simultaneously with gait analysis underwent clinical evaluation and assessment in the following clinical scales: Fugl–Meyer subscale for lower extremity (FMKKD), FM Balance, Lower Extremity Section of the Rivermead Motor Assessment scale (RMANIT), Gross Motor Function Section of Rivermead Motor Assessment scale (RMAFG), Fugl–Meyer (FM), Rivermead Motor Assessment (RMA), Berg Balance Scale (BBC) [11]–[14]. The same physiotherapist was testing all patients and that person did not take part in physiotherapy program of observed patients. The clinical evaluation and gait analysis with kinetic data capture was done on the same day. The results of scale scores from the first clinical evaluation were used to group patients in "better" and "worse" groups. Medial score ($\hat{s}$) of the results of patients in each scale was calculated. If patient's score was below ($\hat{s}$ – 0.1 $\hat{s}$) the patient was included to the "worse" group. If patient's score was over ($\hat{s}$ + 0.1 $\hat{s}$), the patient was included to the "better" group. Patients with results in the interval ($\hat{s}$ – 0.1 $\hat{s}$, $\hat{s}$ + 0.1 $\hat{s}$) were excluded from further analysis. The number of patients in groups created according to the clinical scales: FMKKD, FM Balance, RMAFG, RMANIT was as follows: "better" groups – 13, 13, 31, 18, "worse" groups – 23, 17, 9, 19. respectively.

Statistics

The normality of the variables – GRF signal correlation coefficient and patient's speed expressed as percentage of reference healthy subjects' speed (speed %) was checked using the Kolmogorov–Smirnov and Shapiro–Wilk tests. Variables were summarized by medians and ranges or means and standard deviations (depending on the type of distribution). For evaluation the changes of variables with time the Friedman ANOVA for repeated measures was used. All correlations were calculated as *R* Spearman correlation coefficient. All calculations were performed using Statistica (StatSoft) software.

3. Results

In all tables and plots the GRF components were named in a uniform way, e.g., XP1 means: first letter: component of GRF (X – med/lat, Y – fore/aft, Z – vertical), second letter: P – paretic or N – non-paretic leg, the number is the number of session.

Only fore/aft ground reaction coordinate of non-paretic leg during second session (YN2) was normally distributed, the other variables were non-normally distributed. Table 1 presents the summary of non-normally distributed *R* correlations. The only normally distributed data for YN2 is 0.84 ± 0.07.

The Friedman ANOVA test was performed for "better" and "worse" groups of patients (division according to clinical scales) to examine if GRF changed with time. The results are presented in Table 2. Statistically significant changes are marked with grey. Figure 1 presents respective box plots. Statistically important changes are seen in data of non-paretic leg of "worse" patients regardless of the scale used for classification of patients. In "better" group of patients significant changes are seen only in the case of *Z*-coordinate and also only in non-paretic leg but only when FMKKD and RMAFG scales were used for patient classification. Signal coefficient of correlation with normal data increase with time and as a result more patients are gathered near median value. In "worse" patients group the most significant changes are observed when RMAFG and RMANIT scales were used for classification of patients. An increase between the third and first session (expressed as % of the result obtained during first session) in medio-lateral (*X*) component is 70% (RMAFG, change from 0.40 to 0.68) and 27% (RMANIT, change from 0.53 to 0.67) and in vertical (*Z*) component 34% (RMAFG, change from 0.65 to 0.87).

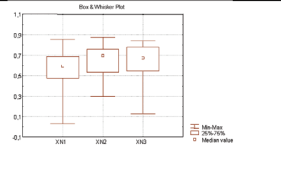
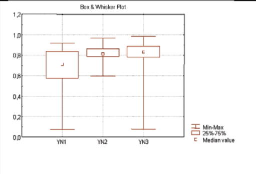
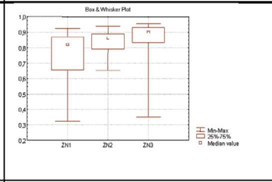
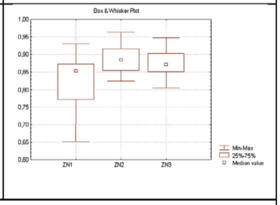
Table 1. Summary of non normally distributed GRF signal correlation coefficient *R*

	Median	Min	Max
XP1	0.79	0.15	0.88
XP2	0.79	0.31	0.89
XP3	0.80	0.41	0.93
XN1	0.61	0.02	0.85
XN2	0.71	0.23	0.89
XN3	0.73	0.12	0.88
YP1	0.84	0.23	0.98
YP2	0.87	0.18	0.97
YP3	0.87	0.05	0.95
YN1	0.81	0.07	0.94
YN3	0.84	0.08	0.98
ZP1	0.82	0.15	0.96
ZP2	0.87	0.26	0.98
ZP3	0.87	0.34	0.96
ZN1	0.84	0.32	0.96
ZN2	0.86	0.65	0.96
ZN3	0.88	0.35	0.95

Kinematics was also captured during the study. The speed % was a non-normally distributed variable. Summary of normalized speed (speed%) according to scales is presented in Table 3.

Table 2. The Friedman ANOVA test results – assessing changes with time in groups (clinical scales)

FMKKD					FMBalance				
	"Worse"		"Better"			"Worse"		"Better"	
	Chi^2		Chi^2	$p <$		Chi^2		Chi^2	$p <$
XP	2.3750	0.3050	1.1667	0.5580	XP	5.1667	0.0755	0.4615	0.7939
XN	7.1250	0.0284	2.1818	0.3359	XN	10.1667	0.0062	0.5000	0.7788
YP	2.2353	0.3271	3.1667	0.2053	YP	5.6923	0.0581	1.8462	0.3973
YN	7.4118	0.0246	2.1818	0.3359	YN	6.0000	0.0498	2.1667	0.3385
ZP	4.6250	0.0990	2.1667	0.3385	ZP	4.6667	0.0970	2.4615	0.2921
ZN	13.8750	0.0010	7.0909	0.0289	ZN	8.6667	0.0131	1.5000	0.4724
RMAFG					RMANIT				
	"Worse"		"Better"			"Worse"		"Better"	
	Chi^2		Chi^2	$p <$		Chi^2		Chi^2	$p <$
XP	2.0000	0.3679	0.6923	0.7074	XP	1.6000	0.4493	2.0000	0.3679
XN	8.0000	0.0183	2.2400	0.3263	XN	13.7333	0.0010	0.4000	0.8187
YP	3.0000	0.2232	0.0769	0.9623	YP	3.1250	0.2096	0.3750	0.8290
YN	7.0000	0.0302	3.4400	0.1791	YN	14.0000	0.0009	1.6000	0.4493
ZP	3.7143	0.1561	4.8462	0.0887	ZP	2.8000	0.2466	3.3750	0.1850
ZN	6.0000	0.0498	9.3600	0.0093	ZN	8.4000	0.0150	1.7333	0.4204

FMKKD		
WORSE_XN	WORSE_YN	WORSE_ZN
		
BETTER_XN	BETTER_YN	BETTER_ZN
NS	NS	
FM Balance		
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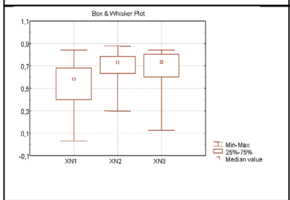	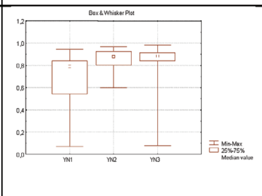	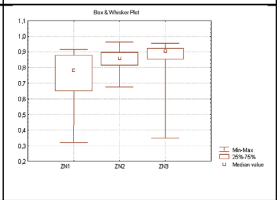
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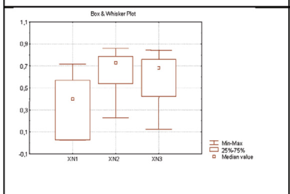
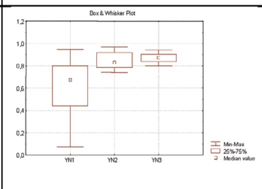
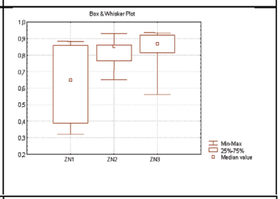
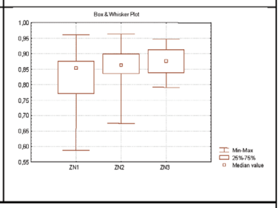
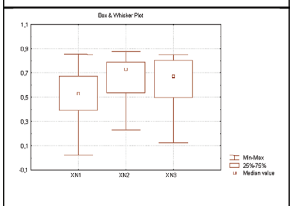
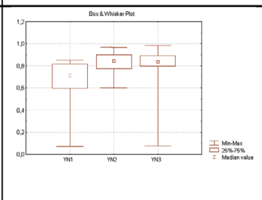
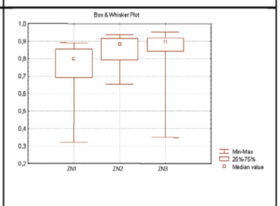
NS	NS	NS
RMAFG		
WORSE_XN	WORSE_YN	WORSE_ZN
		
BETTER_XN	BETTER_YN	BETTER _ZN
NS	NS	
RMANIT		
WORSE_XN	WORSE_YN	WORSE_ZN
		
BETTER_XN	BETTER_YN	BETTER _ZN
NS	NS	NS

Fig. 1. Boxplot of changes with time in all the groups ("worse" and "better" patients) according to different clinic of variables with statistically significant changes. NS – no statistical significant changes

Table 3. Summary of normalized (speed %) grouped on "worse" and "better" patients according to scales FMKKD, FMBalance, RMAFG, RMANIT

Scale	Group	Time point	Median	Min	Max
FMKKD	"better"	1	48.25	20.30	66.40
	$Chi^2 = 12.66667$	2	57.15	21.20	85.30
	$p < 0.00178$	3	58.50	28.80	81.60
	"worse"	1	22.70	4.80	75.90
	$Chi^2 = 32.98795$	2	33.60	17.80	72.80
	$p < 0.00000$	3	38.40	19.50	90.00
FMBalance	"better"	1	43.20	25.60	58.60
	$Chi^2 = 16.76923$	2	60.00	33.80	87.20
	$p < 0.00023$	3	66.40	36.80	98.40
	"worse"	1	20.30	4.80	75.90
	$Chi^2 = 24.87719$	2	34.50	22.70	63.60
	$p < 0.00000$	3	50.90	27.20	90.00
RMAFG	"better"	1	40.80	11.00	66.40
	$Chi^2 = 37.37391$	2	55.00	21.20	87.20
	$p < 0.00000$	3	57.50	28.80	98.40
	"worse"	1	16.30	4.80	75.90
	$Chi^2 = 13.26667$	2	33.10	11.80	53.40
	$p < 0.00132$	3	42.25	19.50	85.30
RMANIT	"better"	1	40.80	20.30	66.40
	$Chi^2 = 26.35821$	2	55.10	21.20	85.30
	$p < 0.00000$	3	57.50	28.80	87.30
	"worse"	1	16.90	4.80	75.90
	$Chi^2 = 25.84848$	2	31.80	11.80	69.60
	$p < 0.00000$	3	33.90	19.50	85.30

Figure 2 presents respective box plots. The changes of speed % with time are statistically significant for "worse" and "better" patients and all the groups. Changes of GRF signal correlation coefficient matrix were statistically significant in the case of "worse" patients, speed % was analysed only in this group. The increase between the third and first session related to the results obtained during first session [%] in that group was: minimum change 70% (FMKKD), maximum 160% (RMAFG), and intermediate 100% (RMANIT), 150% (FMBalance).

The GRF results revealed that the highest changes occurred when patients were divided according to two scales: RMAFG and RMANIT. Therefore the dependence between those two scales was checked using R Spearman correlation coefficient. The results showed that they were dependent: $R = 0.72$ $p \le 0.01$ (first and second sessions) and $R = 0.73$ $p \le 0.01$ (third session). Thus both scales are complementary in the assessment of stroke patients. Results of Table 2 show that statistically significant changes are seen generally in the "worse" groups. Therefore, R Spearman correlation coefficient between GRF signal correlation coefficient and speed% for the group of "worse" patients pooled together from RMAFG and RMANIT was calculated and is presented in Table 4. Statistically significant

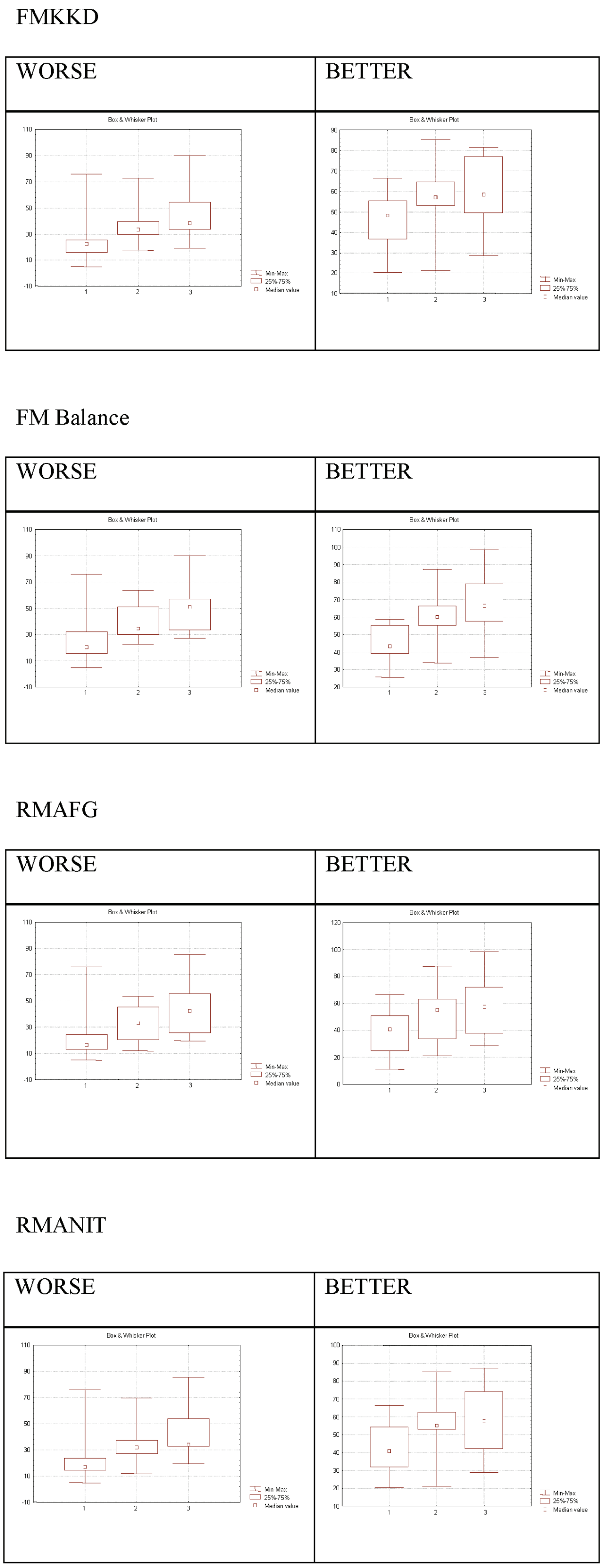


Fig. 2. Boxplot of coefficient (speed %) for groups "better" and "worse" patients according to scales FMKKD, FMBalance, RMAFG, RMANIT in time point

Spearman correlations are marked with grey colour. Some of the links are moderate $R = 0.49$ (X coordinate of non-paretic side during 2 session), some are strong max. $R = 0.72$ (X coordinate of non paretic side during 1 session). All R values decrease with time.

Table 4. R Spearman correlation coefficient between GRF signal correlation coefficient and speed % for "worse" patients group pooled together from RMAFG and RMANIT in reference to paretic and non paretic side

Coordinate		Time point	R	p
Non-paretic	X-coordinate	1	0.72	0.001211
		2	0.49	0.031982
		3	0.32	0.174985
	Y-coordinate	1	0.69	0.001598
		2	0.67	0.001627
		3	0.19	0.434851
	Z-coordinate	1	0.55	0.021204
		2	0.41	0.083719
		3	–0.27	0.259850
Paretic	X-coordinate	1	0.47	0.054093
		2	0.30	0.209283
		3	0.12	0.618850
	Y-coordinate	1	0.71	0.000946
		2	0.21	0.395116
		3	0.36	0.133298
	Z-coordinate	1	0.68	0.002818
		2	0.64	0.003366
		3	0.28	0.241117

4. Discussion

Platforms measuring ground reaction forces during gait are frequently installed in many rehabilitation departments as these departments usually cannot afford full gait analysis systems. But each rehabilitation treatment should be objectively evaluated and one of the methods used for such evaluation could be GRF analysis. Despite of the type of equipment, the method of analysing GRF curves is also important. Digital analysis of characteristic points of curves of GRF components in three dimensions is the method most often used [15], but its disadvantage is that only comparison of each parameter separately is possible. Each of them can change in different way and such analysis does not provide any general value that clearly proves improvement or deterioration of patient's functional status. Harmonic analysis allows whole GRF curves to be analyzed [16], [17]. In this study, the signal correlation coefficient matrix method was applied for the first time to analyze GRF. Advanced mathematical procedure is the shortcoming of both methods. Their application requires longer time from exam to final results.

Results of this study revealed that the statistically significant changes occurred in non-paretic leg of "worse" patients subgroup. Bowden et al. [18] proved that propulsion ratio of patients with severe hemiparesis has value of 20% of that reached by mild hemiparesis patients and also speed is reduced in these patients, to 30%, respectively. Additionally, Olney et al. [19] suggested that the paretic leg, regardless of severity of hemiparesis, performs 40% of the mechanical work of walking, as calculated from kinetic analysis based on intersegmental joint powers. "Worse" patients have to develop more compensating mechanisms in non-paretic legs at the beginning of rehabilitation. As soon as they regain control over paretic leg functions (but not in statistically significant way, according to GRF) they also generally normalize non-paretic leg movement: it comes closer to the normal movement stereotype.

Speed is often used to assess the efficiency of the gait pattern [20]. In our study it was also used to validate the GRF changes. Capability of changes of GRF signal correlation coefficients with time was similar to changes observed in the normalized speed (Fig. 1 and Fig. 2). Changes of GRF signal correlation coefficient of non-paretic side of "worse" patients are not so significant as changes of speed % in that group and statistically significant correlation was observed in the case of the first and second sessions (Table 4). There was no statistical significant correlation between GRF and speed % during the third session. That is because GRF reflects only a part of patient's mobility and kinematics. Step length is determined by kinematics (e.g. hip range and knee flexion in sagittal plane or pelvic range in transverse plane) and strongly influences speed. These kinematic parameters are reflected in GRF as Y coordinate and Z coordinate (as push off phase). As some of the correlations of GRF and speed % are on the borderline of statistical significance the increase in the of number of "worse" patients will validate R values and allow more precise conclusions to be formulated.

GRF are symmetrical in healthy people [17]. Usually full recovery is not possible in stroke survivals, especially in patients with severe hemiparesis, but it is possible to help them to develop compensatory mechanisms in non-paretic side. These mechanisms enable the best possible use of patient's motor potential still available in post-stroke situation. Similar conclusion was emphasized by Roby-Brami et al. in paper related to upper extremity assessment in post-stroke patients [21].

The shortcoming of this study is the number of participants. There are 9 "worse" participants in one group and 13 "better" in another. So that the conclusions of this study are slightly limited, however, the number of stroke patients we included and period of time they were under observation during controlled process of rehabilitation are so far unique.

5. Conclusions

Signal correlation coefficient matrix used for ground reaction force analysis can be used as a method of objective validation of the rehabilitation process in stroke patients but only in patients with "worse" scores obtained in clinical scales. GRF should not be used as the only objective method for full objective validation of patient's status.

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