

# Objectively Characterized Linear Model of Stroke Induced Joint Synergies in Relation to Clinical Measures

Aimen Al-Refai, Matt Simkins, Nancy Byl, Gary Abrams, and Jacob Rosen

**Abstract**—Subjective kinematic motion analysis done by a trained physical therapist using standard assessment such as the Fugl-Meyer assessment (FM) and/or the Wolf Motor Function test (Wolf), have a limited ability to objectively characterize post stroke movement of subjects with a hemiparetic limb or demonstrate fine change over time. The goal of the research was to take the characterized synergies linear matrix model and find an application with stroke survivors. Twenty-two participants were tested for motor impairment using a modified FM (MFM) assessment. Motion capture data was collected using the Vicon motion capture system. This data was processed using Vicon BodyBuilder and MATLAB to construct a stroke subject's Synergy Matrix (SM) from which was developed the Synergy Matrix Score (SMS). This score is compared with the MFM score in terms of efficacy of accepted assessment standards, precise quantitative data, sufficient sensitivity to characterize change over time, and usefulness for clinical reporting. The results show that the SMS provides comparable accurate assessment of the subjects post stroke motion with a high level of sensitivity and greater description of shoulder, elbow, and wrist information in the form of a seven by seven matrix. The SM scoring scale  $(0, \infty)$  also has the ability to quantify change over time at a finer resolution than the MFM range of 0-2 (33% banding) or the Wolf range of 0-4 (25% banding). Results also show that the SMS objectively generates a relevant score comparable to the MFM while maintaining a greater resolution of detail and density of information allowing the physical therapist to better target therapies as well as spend more time working with patients and less time spent on documentation. Adding the SMS to a control system on a therapeutic robot will further automate the SMS into a realtime feedback loop as applied, for example, to stroke prognosis of the targeted therapy.

## I. INTRODUCTION

A motor deficit impairs the ability to move the stroke-affected limb or side otherwise known as, hemiparesis. Due to this limitation, survivors experience decreased autonomy and quality of life [1]. An aspect of diminished coordination

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is joint synergies [2]. “Joint synergies” is synonymous with “muscle synergies” that are the result of stroke damage in humans. “Joint synergy” has been used in the literature as having both positive connotations and negative connotations on motor function. A “efficacious” synergy implies that a healthy individual can move multiple joints in a coordinated way such that complex motion, such as running or throwing, is performed in a fluid and precise way. A “deleterious” synergy implies that the individual performs involuntary motions that hinder fluid and precise movements. Upper-limb synergies have certain stereotypical synergies that affect the movements of the trunk, scapula, shoulder, elbow, wrist, and hand [2]. This study considers only the shoulder, elbow, and wrist joints. Thus, the human arm is modeled as a seven degrees of freedom (DOF) manipulator.

It is known that, by working intensely following stroke with a trained clinician, those suffering from hemiparesis can often regain partial use of the affected limb [3]. In order for clinicians to quantify the level of hemiparesis and the efficacy of rehabilitation, suitable assessment tools were developed. Two such tools, the Fugl-Meyer Upper Extremity Assessment (FM) [4] and the Wolf Motor Function Test (Wolf) [5], are considered the gold standard of assessment tools. However, the Wolf and FM have limited objective ability to characterize movement [6], [7]. Assessment measures used in intervention research are often focused on task completion or clinician ratings of movement. These results are limited in specific, precise, and quantitative data that effectively distinguishes remediation of deficits versus the development of compensatory movement therapies. The functional significance of a stroke survivor's ability to complete meaningful tasks should not be undermined, yet these types of outcome measures do not provide information regarding specific movement [7].

The Wolf is a common task-based outcome measure that has become one standard measure in research investigations of upper-extremity rehabilitation interventions such as constraint-induced therapy (CIT) [8]. The Wolf incorporates gross- and fine-motor components of all joints in a variety of functional tasks such as reaching for a can, picking up a pencil, or folding a towel. The instructions for each task emphasize speed of completion and all tasks are videotaped for subsequent rating of functional ability. Functional ability is rated on a 5-point ordinal scale that incorporates task completion and generalizations regarding movements made in synergy. The Wolf also includes two strength measures but these are reported less in the scientific literature. The

Wolf has established reliability as a stroke assessment and research tool [9], [10], [11], [12].

The FM is another common measurement tool used in stroke rehabilitation. In addition to evaluating some basic movement tasks or task components (e.g., gripping a can or ball, holding a pencil with a two-point pinch), the FM assessment also evaluates more basic movement capacities foundational to task performance on a 3-point ordinal scale. For example, subjects are instructed to produce isolated shoulder movements while maintaining elbow extension during which an evaluator rates movement capacity (See Fig. 3). Other scored criteria include the presence of reflexes, tremor, dysmetria, and speed of movement. The FM has established validity and reliability as a research tool [13], [14], [15]. Together, the Wolf and FM assessments provide valuable information regarding motor performance and motor impairment after stroke, yet they do not objectively yield precise quantitative data on movement synergies and lack sufficient sensitivity to characterize changes over time.

The purpose of this study is to quantify functionality of a stroke survivor such that the outcome measures provide an accurate description of the stroke survivor's movement synergies and show sufficient sensitivity to characterize changes over time as the subject is reassessed as therapy progresses.

## II. METHODS

### A. System

The Vicon MX motion capture system [16] was used to record reflective infra-red marker locations in a calibrated target volume. Ten ceiling mounted MX cameras pointed at a calibrated target volume centered on the subject's arm. The calibration wand set up the reference (x, y, z) origin from which was derived the standard Denavit-Hartenberg parameters for the 7 DOF. Fourteen markers in total were attached to the subjects right or left arm and torso. Ten arm markers were attached to bare skin and four markers attached to a shirt that was taped snug to the body as depicted in Fig. 1(a), 1(b) and Fig. 2. The marker placement is particularly sensitive due to the needs of the Nexus' model template applied to the raw data. Following the template's desired positions ensures accurate results. The subjects were seated on a metal chair with a backrest and no arm rests. The subject's torso was held in place with duct tape that wrapped around the subject's abdomen and backrest of the chair. With respect to the taping of the torso, it is important to note that results from [17] suggest that there is no strong relationship between the amount of trunk use and functional performance of the subsequent asked for action. Thus, the purpose of limiting torso lateral movement was to help with isolating joint movement and core stability. All arm motions started and ended from the same position as depicted in Fig. 2. The sampling rate of the cameras was set to 100 Hz. Joint angles were extracted from marker position data using custom code written in Vicon Bodybuilder. Joint angle information was then processed using various MATLAB scripts.

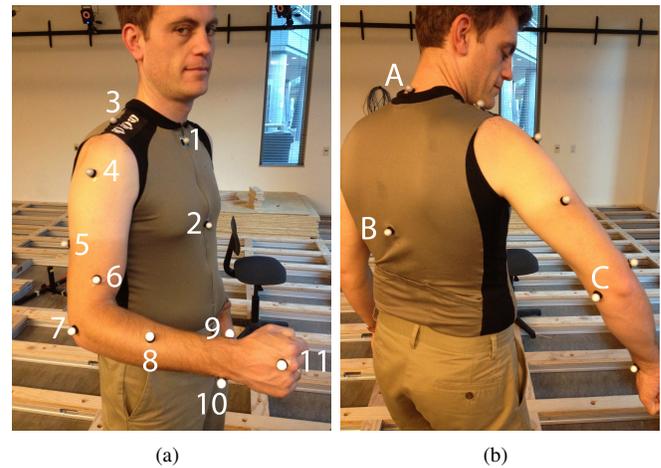


Fig. 1. (a) 1=jugular notch where clavicles meet the sternum, 2=xiphoid process of the sternum, 3=acromio-clavicular joint, 4=lateral lower belly of the deltoid (asymmetric with 5 and 6), 5=distal end of triceps outer head (asymmetric with 4 and 6), 6=distal end of the long head of the bicep brachii (asymmetric with 4 and 5), 7=lateral humerus epicondyle approximating the elbow joint axis, 8=insertion point of the anconeus, 9=thumb side of the radial styloid (symmetrical with 10 to form an axis through center of wrist), 10=little finger side of ulnar styloid (symmetrical with 9 to form an axis through center of wrist) (b) A=7th cervical vertebra, B=10th thoracic vertebra, C=medial humerus epicondyle approximating the elbow joint axis

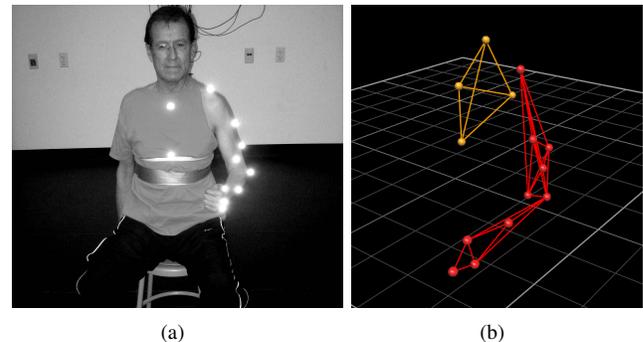


Fig. 2. Experimental setup for stroke survivor with left-side hemiparesis. Pictured in (a) is the standard start position. Pictured in (b) is the subject-specific arm model.

### B. Subjects

Twenty-two subjects participated in this study. Eleven healthy control subjects and 11 stroke affected subjects. Of the 11 healthy male control subjects, five were age-matched because age was a possible confounding factor. The age-matched ages ranged from 61 to 77 years old. The remaining six ages ranged from 19 to 45 years old. The control subjects had no history of strokes and were neurologically intact. Control candidates with arm/shoulder injuries or neurological damage were excluded. Healthy subjects performed arm motions using their dominant arm.

Eleven hemiparetic subjects participated in the study, six female and five male, ages ranging from 54 to 82 years old. All stroke survivors were in their chronic phase of recovery. The number of years since their most recent stroke ranged from 1 year to 15 years. All stroke subjects were screened

with a phone interview prior to being scheduled for testing to ensure they met the minimum set of requirements to participate in this study. The candidate was rejected if the candidate's impairment was too mild; if the candidate had fully recovered; if the impairment was caused by an injury other than a stroke, (i.e. head trauma); if the stroke was less than two months old; if the candidate has no range of motion or less than ten degrees for arc in the candidate's shoulder, elbow, and wrist. The reason for this last requirement is that this study uses the FM as a comparison standard to corroborate efficacy of the SM. The FM requires the candidate to have the ability to straighten the arm (See Fig. 3(b)) as well as the ability to maintain the desired start position (See Fig. 3(f)). If the start position cannot be executed by the candidate, then the FM assessment cannot be done[4]. Therefore, if the candidate could not complete the FM assessment the candidate's results could not be compared to an existing standard, and the candidate was ineligible to take part in this experiment.

The resulting sample population was intended to have as diverse a range of hemipareses as possible while ensuring that subjects had enough range-of-motion in the subject's affected arm to generate meaningful motion capture data. In other words, the stroke affects were severe enough that the subject's arm demonstrated measurable joint synergies. Table I has statistical biometric data of experimental subjects. The research was approved by the University of California, Santa Cruz, Internal Review Board. All subjects provided written consent prior to study participation. Gender was not anticipated to be a factor and was not controlled for in the data collected.

TABLE I  
BIOMETRIC DATA OF EXPERIMENTAL SUBJECTS ( $n = 22$ )

Health Age (years)	$\bar{x} = 48.5(\pm 22.4)$
Stroke Age (years)	$\bar{x} = 65.5(\pm 8.4)$
Time since stroke (years)	$\bar{x} = 7.6(\pm 5.3)$
Side of Infarct	3 LCVA 8 RCVA
Gender	6 females 16 males

LCVA: left cerebrovascular accident.  
RCVA: right cerebrovascular accident.

### C. Protocol

Control and hemiplegic subjects performed 21 arm movements in total. Using the start position depicted in Fig. 2, subjects were asked to perform arm movements that focused on one joint at a time, until all seven joints were moved. Every iteration through the seven joint movements is considered a set. All subjects completed at least three sets. All subjects also performed a modified Fugl-Meyer assessment (MFM) which has seven arm motions as well. The performed actions for the experiment and the MFM are shown in Fig. 3 and summarized in Table III. The experiment took approximately 60 to 90 minutes for each subject. The actual data collection took approximately 15 minutes.

### D. Data Analysis

1) *Model*: The seven MFM arm motions are selected from the 22 total motions available in the full FM assessment. These selected arm motions match the joint focused motions developed for the experiment. Fig. 3 depicts the side-by-side comparison. The reason for this is to minimize the difference between the asked for articulation of each joint allowing for discussion on the success or failure of the actual SMS data.

Negative joint synergies are characterized by the involuntary co-activation of joints. As such, if an individual attempts to move one, and only one joint, then the existence of joint synergy among the other joints implies that some or all of the other joints in the arm will also move in response to the intended joint movement. If it is assumed that joint one is arbitrarily designated as the single joint intentionally moved, then the response can be represented as a column vector,  $\vec{R}_1$ ,

$$\vec{R}_1 = [f_{11}(x_1) \ f_{21}(x_1) \ f_{31}(x_1) \ f_{41}(x_1) \ f_{51}(x_1) \ f_{61}(x_1) \ f_{71}(x_1)]^T \quad (1)$$

where  $f_{11}(x_1)$  denotes the response of joint one to an attempted motion (or as a function) of joint one,  $f_{12}(x_1)$  denotes the response of joint two as a function of joint one,  $f_{13}(x_1)$  denotes the response of joint three as a function of joint one, and so on up to joint seven. Likewise, the same procedure is performed on the next joint to generate  $\vec{R}_2$ .

Physically, column vectors,  $\vec{R}_j$ , are generated experimentally by asking the subject to move a single joint in an isolated movement and then simultaneously record the response of the other six joints. Likewise, the same procedure is performed for joint two, joint three, and so on. After carrying out this procedure for all seven joints the resulting functions can be expressed as the following matrix,

$$\hat{y} = [\vec{R}_1 \ \vec{R}_2 \ \vec{R}_3 \ \vec{R}_4 \ \vec{R}_5 \ \vec{R}_6 \ \vec{R}_7] = \quad (2)$$

$$\begin{bmatrix} f_{11}(x_1) & f_{12}(x_2) & f_{13}(x_3) & f_{14}(x_4) & f_{15}(x_5) & f_{16}(x_6) & f_{17}(x_7) \\ f_{21}(x_1) & f_{22}(x_2) & f_{23}(x_3) & f_{24}(x_4) & f_{25}(x_5) & f_{26}(x_6) & f_{27}(x_7) \\ f_{31}(x_1) & f_{32}(x_2) & f_{33}(x_3) & f_{34}(x_4) & f_{35}(x_5) & f_{36}(x_6) & f_{37}(x_7) \\ f_{41}(x_1) & f_{42}(x_2) & f_{43}(x_3) & f_{44}(x_4) & f_{45}(x_5) & f_{46}(x_6) & f_{47}(x_7) \\ f_{51}(x_1) & f_{52}(x_2) & f_{53}(x_3) & f_{54}(x_4) & f_{55}(x_5) & f_{56}(x_6) & f_{57}(x_7) \\ f_{61}(x_1) & f_{62}(x_2) & f_{63}(x_3) & f_{64}(x_4) & f_{65}(x_5) & f_{66}(x_6) & f_{67}(x_7) \\ f_{71}(x_1) & f_{72}(x_2) & f_{73}(x_3) & f_{74}(x_4) & f_{75}(x_5) & f_{76}(x_6) & f_{77}(x_7) \end{bmatrix}$$

The elements of column vector  $y$  in (2) describes the response angle as a function of the seven input angles, including the joint that is being moved. The relationship between the joint that a subject attempts to move compared to the way that joint actually moves is difficult, and perhaps impossible to know. In order to simplify the model, it is assumed that the response angle for the joint being intentionally moved, is equal to the desired angle. Therefore, for  $i = j$ ,  $f_{ij}(x_j) = 1$ , where  $i$  is the  $i^{th}$  row and  $j$  is the  $j^{th}$  column. If such a matrix could accurately represent joint synergies then one could predict the arm trajectories of a paretic arm using  $\hat{y}$  given any combination of desired input angles. Assume that the starting angles of a given reaching movement all begin at zero, and that these functions can be approximated by a linear polynomial model which sufficiently characterizes the



Fig. 3. All image sequences show start and stop positions with actions in-between. a, c, e, g, i, k, m are synergy matrix motions while b, d, f, h, j, l, n are Fugl-Meyer assessment actions. The MFM motions are selected to best match synergy experiment motions.

synergy, then

$$\hat{y} = \sum_{k=0}^n \vec{A}(k) \vec{x}^k \quad (3)$$

where  $n$  is the order of the polynomial model and  $A(k)$  is the matrix of coefficients of the  $k^{th}$  ordered term. The zero order term  $A(0)$  includes the start position angles which are arbitrarily assigned. If it is assumed that the start/end positions are approximately the same then  $A(0)$  is not especially important for these purposes, and is thus ignored. Because the output of the desired joint is assumed to equal the desired rotation, the  $1^{st}$  order matrix  $A(1)$  always has ones on the diagonal. Higher order terms,  $A(2)$  through  $A(n)$ , will have zeros on the diagonal. In this study, a linear model was used. Linear ( $n = 1$ ), quadratic ( $n = 2$ ), and cubic ( $n = 3$ ) model fits are further evaluated in Simkins' paper [18]. In this case the linear model is

$$\hat{y}_{linear} = \vec{A}(1) \vec{x} + \vec{A}(0) = \quad (4)$$

$$\vec{A}(1) \vec{x} = \begin{vmatrix} 1 & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & a_{17} \\ a_{21} & 1 & a_{23} & a_{24} & a_{25} & a_{26} & a_{27} \\ a_{31} & a_{32} & 1 & a_{34} & a_{35} & a_{36} & a_{37} \\ a_{41} & a_{42} & a_{43} & 1 & a_{45} & a_{46} & a_{47} \\ a_{51} & a_{52} & a_{53} & a_{54} & 1 & a_{56} & a_{57} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & 1 & a_{67} \\ a_{71} & a_{72} & a_{73} & a_{74} & a_{75} & a_{76} & 1 \end{vmatrix} \begin{vmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{vmatrix} \quad (5)$$

where  $A(1)$  gives the coefficients for the synergistic joint responses and  $A(0)$  denotes the start/end angles. The resulting matrix in (5) is sometimes referred to as a covariance matrix and a plot of the slope values is referred to as an interactions plot. For this paper, the matrix is called the synergy matrix (SM) because it describes the interactions of human joints which are discussed in medical literature as synergies [2].

2) *Statistical Analysis:* Statistical analyses were done using Statistics Toolbox from MATLAB. Nonparametric analysis was used for all data not normally distributed such as the Wilcoxon signed rank (paired sample) test for

comparing the healthy SM and MFM scores. The normally distributed SM and MFM stroke scores were compared by Intraclass Correlation Coefficient (ICC), models (1, 2, 3). A repeated measures tool, one-way ANOVA, was performed to corroborate and examine a subject’s intra-trial SM and MFM scores in order to see change over time. For all analyses the chosen values for the criterion alpha level was 0.05, power was 0.84, and difference divided by standard deviation was 0.65. These values allowed for a population of 22 subjects.

### III. RESULTS

Table II has descriptive general statistics for healthy and stroke subjects. The modified FM score is 0-14 where 14 is the top score indicating excellent healthy movement and 0 is indicating poor unhealthy movement. With a population of 22 and three trials or repetitions done, a normal distribution is less certain since the standard minimum population for statistics is greater than 30 [19]. Nevertheless, normal distribution is assumed and the results are reassured by the good fit shown in Table II.

TABLE II  
DESCRIPTIVE STATISTICS ( $n = 22$ )

	Mean	Variance	STDERR
Healthy			
MFM Score	14	1.08002e-12	3.1109e-07
SM Score	11.6364	0.854545	0.278722
Stroke			
MFM Score	7.90909	15.6909	1.19434
SM Score	7	7.4	0.8202

#### A. SM Score vs. MFM Score

The MFM scores of all the healthy subjects, as expected, are 14 (maximum score). Since the healthy subjects’ MFM scores were not normally distributed, a comparison between the healthy SM and MFM scores was done using the Wilcoxon signed rank (paired sample) test. The results show that the null hypothesis; “MFM scores do not match SM scores”, was rejected with a p-value of less than 0.001 as Fig. 4 shows. ANOVA was used to corroborate the result and weakly supported the ICC results with a p-value of 0.2872. As shown in Fig. 5(b), it is evident that the SM scores do track the MFM scores with a plus or minus of two and a half for the healthy, which suggests the subjective hysteresis of clinical assessment of healthy subjects is less efficacious than of the stroke subjects. As a study in contrast, the stroke data was normally distributed. Thus, it was analyzed using ICC. The results show an agreement between SM stroke scores and MFM stroke scores with an ICC equal to 0.8227 as shown in Fig.6. ANOVA was used to corroborate the result and strongly supported the ICC results with a p-value of 0.9034. As shown in Fig. 5(a), the SM scores do track closer than the healthy SM scores with the MFM scores at less than one point variance.

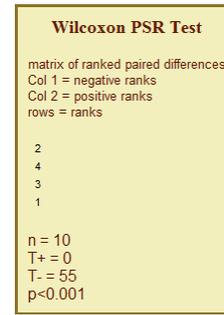


Fig. 4. Nonparameter analysis with Wilcoxon signed rank test on healthy SM mean score and MFM mean score. Image produced by stattools.net.

#### B. Synergy Matrix Data Density

The output,  $\hat{y}_{linear}$ , is the product of SM times the range of each joint as demonstrated in equation (4). The resulting 7x7 matrix has joint angles that express joint synergies characterized by the SM. Fig. 7(a) illustrates the ideal case where the resulting bar graph of the SM has only values on the diagonal and zeros everywhere else. The larger the bar, the greater the joint movement. Averaging all the healthy subjects’ SM into a representative mean healthy “golden standard” SM results in Fig. 7(b), which illustrates the typical healthy synergies allowing humans to move with ease and grace. Fig. 8 shows a stroke subjects’ deleterious SM as compared to the gold standard efficacious SM. The scale of the gold standard SM is set to the max value of the stroke subjects’ SM in order to better compare each image. Subtracting Fig. 8(a) from Fig. 8(b) leaves the residuals. These residuals in Fig. 9 are only those synergies that are deleterious to healthy movement synergies. Note the y-axis values exceed one as normalization was done with the max value of range for the specific joint (row major). Any number above one has deleterious synergies. The x-axis specifies the joint of focus.

TABLE III  
JOINT MOVEMENTS

Joint	Joint No.	Req. Movement	Range (degrees)
Elbow	1	Extension, flexion	160
Wrist	2	Pronation, supination	90
Shoulder	3	Flexion	90
Shoulder	4	Inner/outer Rotation	130
Shoulder	5	Abduction	90
Wrist	6	Flexion	90
Wrist	7	Ulnar deviation	55

130 adjusted from 160 due to stopping at torso contact.

55 adjusted from 90 due to only asking for ulnar deviation

#### C. Sensitivity

The SM provides sensitivity to change over time as well as detail to distinguish differences. The results show in general that all subjects tended to score 1.5 points lower on subsequent trials than the initial SM trail score. The residuals were calculated to show how much performance decays between each trial completed by each subject. Subject

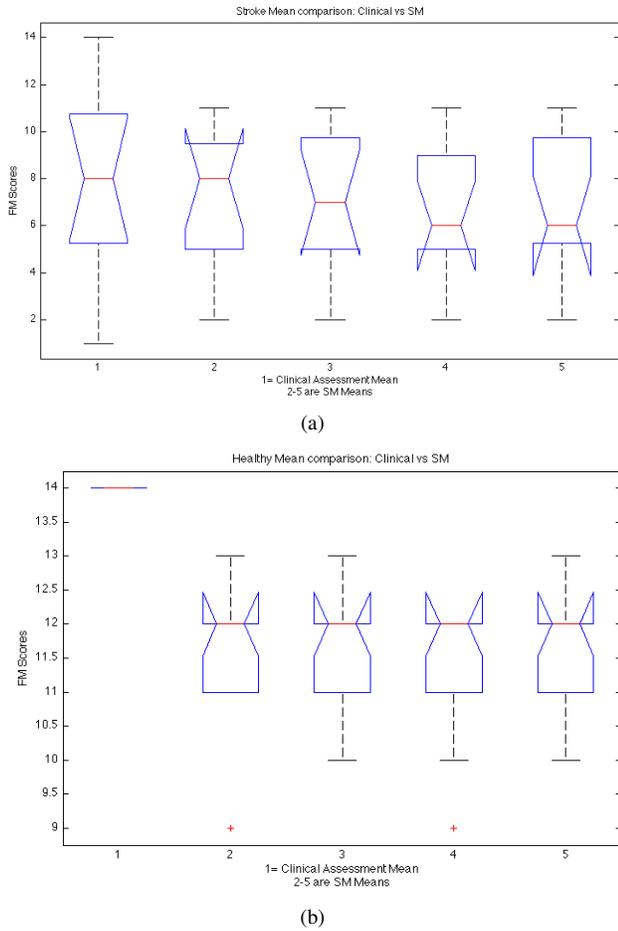


Fig. 5. ANOVA box plots. (a) The SM stroke means compared to MFM stroke mean. (b) The SM healthy means compared to MFM healthy mean.

Analysis of variance					
Source of variance	df	ssq	msq	F	p
Between rows	10	212.4545	21.2455	11.5123	0.0003
Within rows	11	23	2.0909		
Between cols	1	4.5455	4.5455	2.4631	0.0856
Residual err	10	18.4545	1.8455		
Total overall	21	235.4545			

Intraclass Correlations		
ICC	Single	Meaned
Model1	0.8208	0.9016
Model2	0.8227	0.9027
Model3	0.8402	0.9131

Summary of results	
ICC	= 0.8227
Sig of diff between Cols/residual	F = 2.4631 p = 0.0856
Sig of diff between Cols/cases	F = 0.2139 p = 0.6536

Fig. 6. Stroke SM score and MFM score ICC comparison. Image produced by stattools.net.

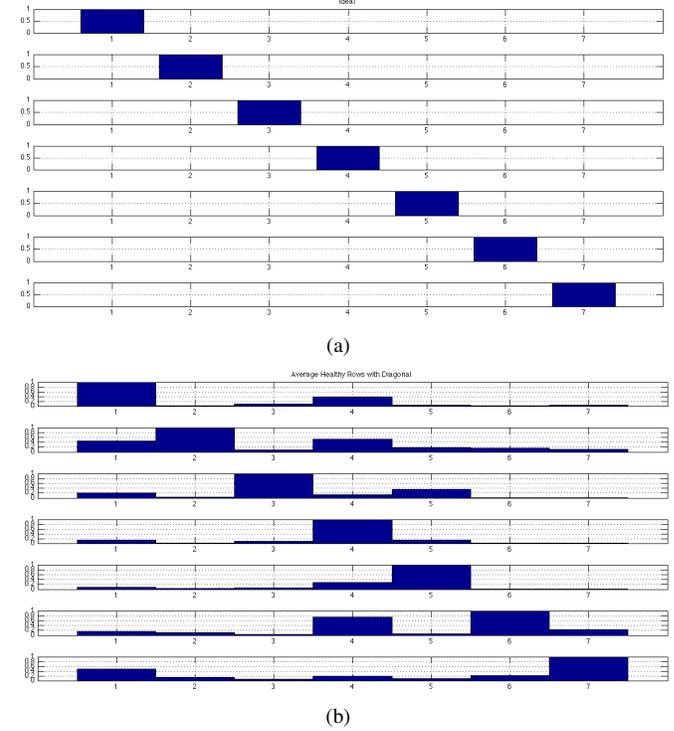


Fig. 7. (a) The ideal input with max range per joint and no synergies. (b) The gold standard SM of all the healthy subjects times the max range per joint.

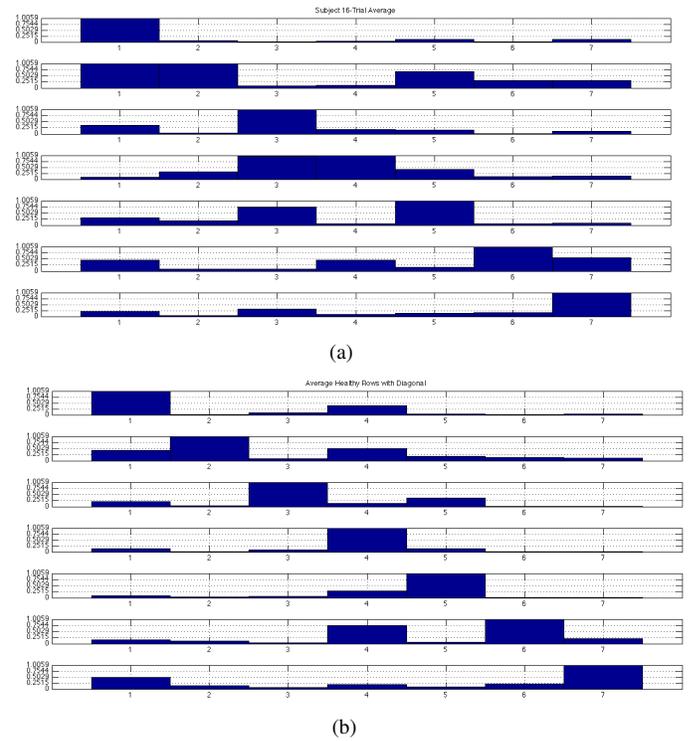


Fig. 8. (a) Stroke subject 16's SM. (b) The gold standard SM with the scale adjusted to match stroke subject 16.

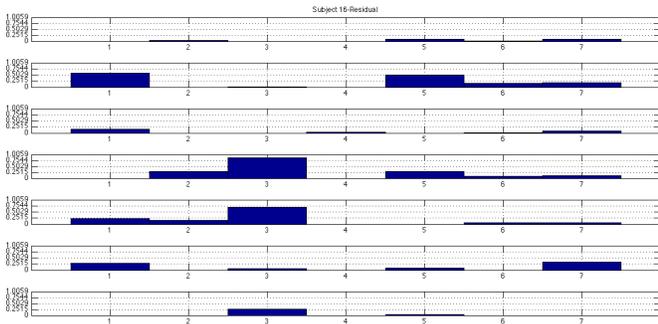


Fig. 9. Subject 16's residuals show strong synergies in joints 1, 3, 5, 7.

4's SM scores are 12, 11, and 11 for trials 1, 2, and 3 respectively. The residuals express the difference between trials 2 and 3 even though they scored an 11. Subject 10's SM scores remained a consistent SM score of 12 through all the trials, yet the residuals show an improvement over time. Fig 10 demonstrates this point.

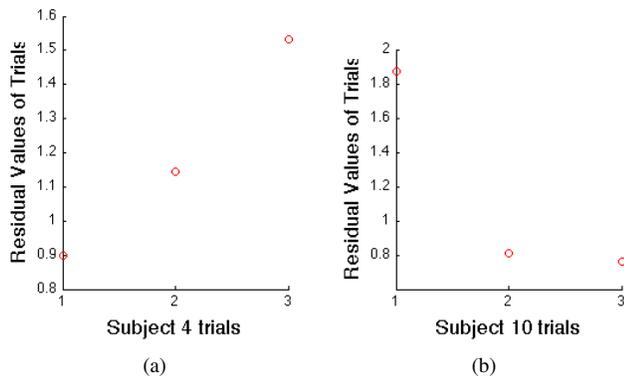


Fig. 10. (a) An increase in synergies is detected. (b) A refinement of synergies is detected.

#### IV. DISCUSSION

The SM score is a number created to corroborate efficacy of the SM as clinical assessment tool. Therefore a natural comparison to an existing clinical standard, such as the FM score, is required. This paper has shown that an objectively collected data set and calculated SM scores closely match the subjective MFM scores. Furthermore, any standard clinical assessment, such as Wolf, can be matched as well. Supporting this statement is the method of calculation. In this paper the calculation is an algorithm, called the SM rules engine, which was created to match the assessment tool desired - in this case the MFM. The SM rules engine for the MFM is as follows in the flow chart, Fig. 11.

Algorithm in Fig. 11 can be written to output matching assessment scores by calculating the range of each joint for the FM, or range of time for Wolf, or a combination from the data. The range is then divided by the ordinal scale of the assessment being used. In the case of FM the ordinal scale is three and by adding two more *if clauses* per joint the range

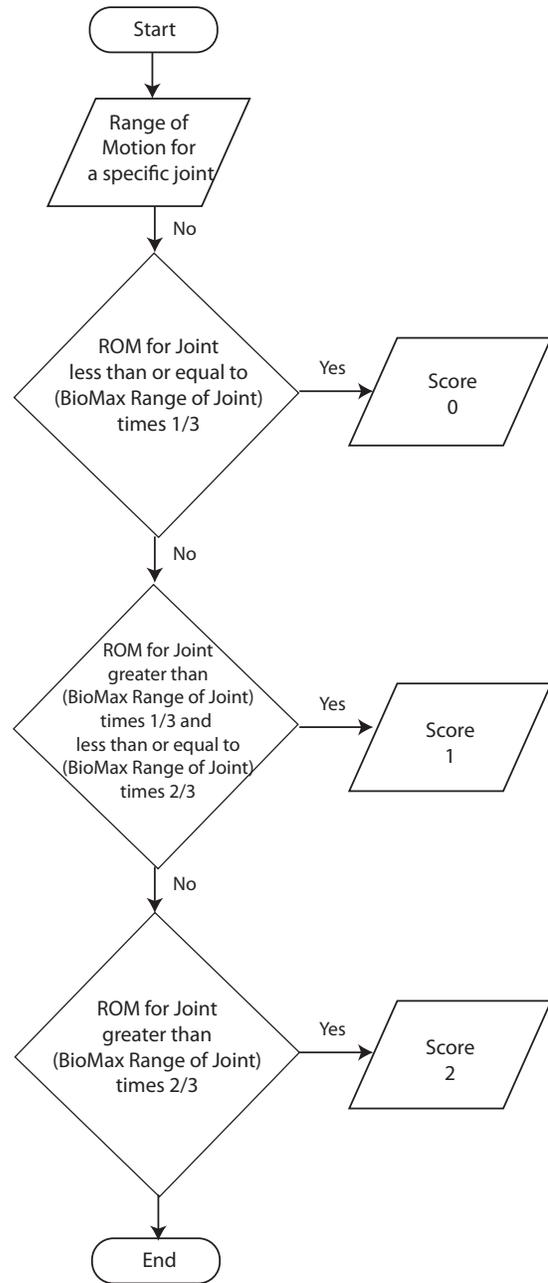


Fig. 11. This is the general SM rules engine for the MFM scoring.

can be divided by five as is the case with Wolf. This crude system was found to fall within the 95% CI. However, there are those actions that don't easily map as in the case of elbow flexion, Fig. 3(g) and Fig. 3(h). Thus, a way to fine tune for the specific assessment is needed.

To fine tune the SM rules engine containing the MFM algorithm, *if clauses* echoed synergistic conditions expressed by the data. Hypothetically, a healthy person has a stroke with a loss of degree of freedom in the wrist. When wrist movement is lost, elbow flexion and shoulder abd/adduction synergies dramatically increase to maintain the workspace of the hand. The algorithm then must reflect this synergistic

conditions expressed by the data as a hysteresis which further bounds the joint actions logic to produce more exact results. Brunnstrom, et al. summarized that there are typical patterns of synergistic responses with loss of degree of freedoms [2]. Fig. 9 supports this finding as empirically observed in the stroke subjects of this experiment.

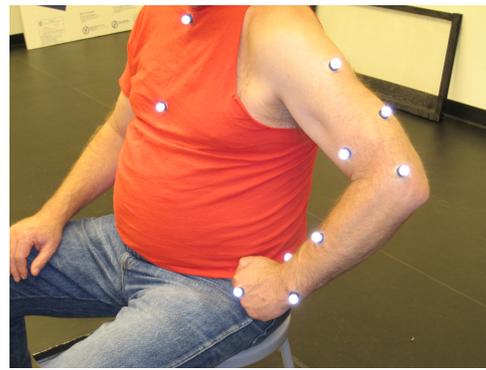
Data is as precise as the hardware that collected it and the software’s limitation of precision. That being said, The SM score which was made to emulate MFM scores tended to be 2.5 points lower for healthy subjects versus within 1 point lower for with stroke subjects. It is argued that this discrepancy is from the clinician’s ability and experience to decide if the MFM score is 0, 1, or 2. For example, Fig. 12 shows a subject attempting to move the back of the hand to the small of the back as way of showing range of motion for inner shoulder rotation. Table IV contains the scoring instructions to the clinician based on the requested action. In Fig. 12(c), the subject could score a 1 or 2 depending on the experience of a clinician. The data calculation being objectively exact tended to be less generous with this score. Even with a hystereses that fine tuned the values from 0 to 1 and 1 to 2, the SM scores tended to be lower. Interestingly, the stroke MFM score closely matched the SM scores implying that greater care was taken with the stroke assessments by the clinician. Further implying that the SM score is more reliable than the MFM score.

TABLE IV  
FM MOVEMENTS

Scoring
0 = Hand does not move posterior to the frontal plane at the location of the anterior superior iliac spine.
1 = Hand does move posterior to the frontal plane at the location of the anterior superior iliac spine.
2 = Hand is placed on the small of the back with equivalent movement quality as the unaffected side.

Referenced from [15]

Due to the richness of data available from the SM, any scale can be developed. For example Fig. 14 is based on the residuals. Fig. 14 shows the difference between healthy subject’s SM minus the gold standard SM as well as the stroke subject’s SM minus the gold standard SM. Clearly evident is the difference between healthy and stroke. However the border cases are the most interesting to examine. Focusing on the difference between healthy subject 7 and stroke subject 22, both show total residual scores of 2.546 and 2.606 (SM scores for subjects 7 and 22 are 13 and 9), respectively. Focusing further on the individual synergies, the clinician can see the individual synergies and how they relate with one another in Fig. 13(a) and Fig. 13(b). This is where a user friendly interface can enhance the information being presented as suggested by Fig. 13. The residual matrix of numbers are assigned a color. The higher the number the more red the color (roygbiv – 1 to 0). Now a clinician can see that Fig. 13(c) shows the subject has strong synergies around shoulder abduction, shoulder flexion and wrist flex, and wrist ulnar deviation. Using Table III to decode the



(a)



(b)



(c)

Fig. 12. Scoring positions (a) = 0 (b) = 1 (c) = 1 or 2? Depends.

column numbers and with some future training on the squares relationships, a clinician can see with the colors that the wrist is held in max ROM in flexion and supination causing recruitment of the shoulder for motion when attempting to do wrist ulnar deviation.

The research is not without its limitations. The model described by (5) makes several important assumptions. First and foremost, this is a kinematic model. As such the model does not include arm dynamics, gravity, forces, or torques. Second, representing the human nervous system and limb anatomy as a geometric function might appear overly simplistic. Ideally, a more complete model based on first principals would likely include factors relating to, at a minimum, the nervous system and biomechanics.

Third, (5) assumes that the same joint relationships apply regardless of the start or end angle. Strictly speaking, the models developed in this paper relate to the start and end positions depicted in Fig. 2.

Fourth, (5) assumes that there exists only one-way interactions between joints and that a greater number of interactions do not exist. To take a physical example, one-way interactions assume that the simultaneous rotation of the wrist and elbow result in the same shoulder response as the combined effect of moving the wrist and elbow by themselves. While interactions greater than one are certainly possible, evaluation of such interactions are very difficult to measure in practice. Stroke survivors often have speech or cognitive effects. Communicating the need for such subjects to move two or more joints simultaneously while holding all other joints fixed was deemed too confusing. Therefore, in the strictest sense this model is most reliably applied to discrete, singular joint movements and it might apply to more complex multi-joint movements such as general reaching.

Fifth, (5) assumes that a single synergistic interaction is the same in the forward rotation direction as in the reverse direction, or that it is reversible. Stated another way, the model assumes that interactions are the same for joint flexion and extension. Note, this model does not assume that the matrices in (5) are symmetric. Even though the classical view of flexor and extensor synergies does not make this distinction, matrices described by (5) were generally not symmetric, i.e. interaction  $(i, j) \neq (j, i)$  for  $i \neq j$ . Assumption one, two, and three are indeterminate using the foregoing protocol. However, the procedure does allow for an evaluation of reversibility. Quantifying reversibility is important because a largely irreversible interaction will result in a poor model fit no matter what model is used or how small the noise is. If irreversibility diminishes the fit enough, then separate functions in the forward and reverse directions would be required. By definition, a joint interaction is non-reversible if the flexion path differs from the extension path. This is never the case for linear interactions, but it is possible for nonlinear interactions.

Lastly, subjects represented only a subset of the stroke population that have some voluntary control and motor function of the stroke affected limb. In particular the ability to extend the elbow. Difficulty extending the elbow after stroke is common and this limitation is clinically observed as part of a flexor synergy pattern that produces concurrent flexion motions, and which also often impairs the stroke subject's ability to control individual joints [20]. Filtering for elbow extension commonly eliminates 20% of the stroke population [21]. A larger sample size would increase external validity by allowing for more generalizations to be made from this research to a population presenting varying degrees of motor impairment.

## V. CONCLUSIONS AND FUTURE WORK

The goal of the research was to take the characterized synergies linear matrix model of a human arm and find an application with stroke survivors. The research successfully

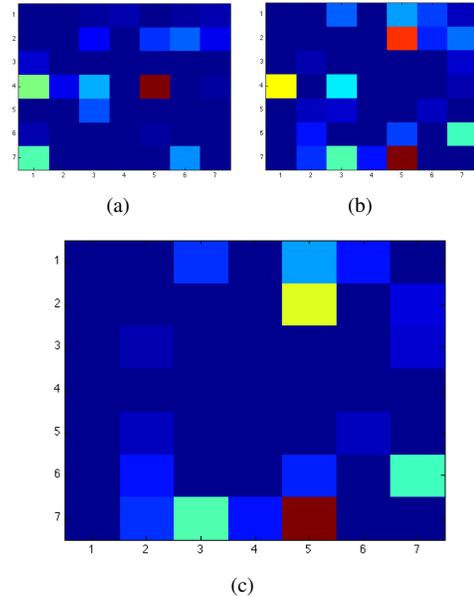


Fig. 13. (a) Show subject 7's residuals. (b) Shows subject 22 residuals.  $(b) - (a) = (c)$  the residuals of b-a

demonstrated an objective way to collect subject data, a novel description of the collected data in a functional matrix model, and a solution that addresses the deficiencies of the standard methods, such as measures of change and prognosis of recovery. By describing stroke synergies as a matrix, it allows for the use of more powerful mathematic tools. Applying these tools for categorizing subjects based on their movements was demonstrated as compared to a modified FM assessment. The SM could be useful in further studies that seek to find more subtle affects of rehabilitation or brain injury, such as physical therapy strategies for symmetric motion. The Vicon motion capture system used for this research is too expensive to use for most clinical settings, however, relatively high quality low cost position sensing devices are now commercially available such as the Microsoft Kinect which could be used to cost effectively gather similar data in a clinical setting.

Such systems could conceivably be used in conjunction with this model to provide finer-grained, more quantitative measures of synergy with better repeatability and reproducibility. Use of these tools and assessment strategies with stroke survivors would dramatically reduce clinical assessment and documentation times and provide increased high quality movement data to allow physical therapists to better focus rehabilitation therapies.

Finally, the methods described in this paper may allow for new types of algorithms for use in robotic physical therapy (RPT), such as an upper limb powered exoskeleton [22]. By the nature of their design, rehabilitation robots typically require high-precision position and force sensing. Implementing the synergy matrix model into the robotic system might allow for continuous monitoring of progress by tracking synergy reduction in stroke survivors. Additionally,

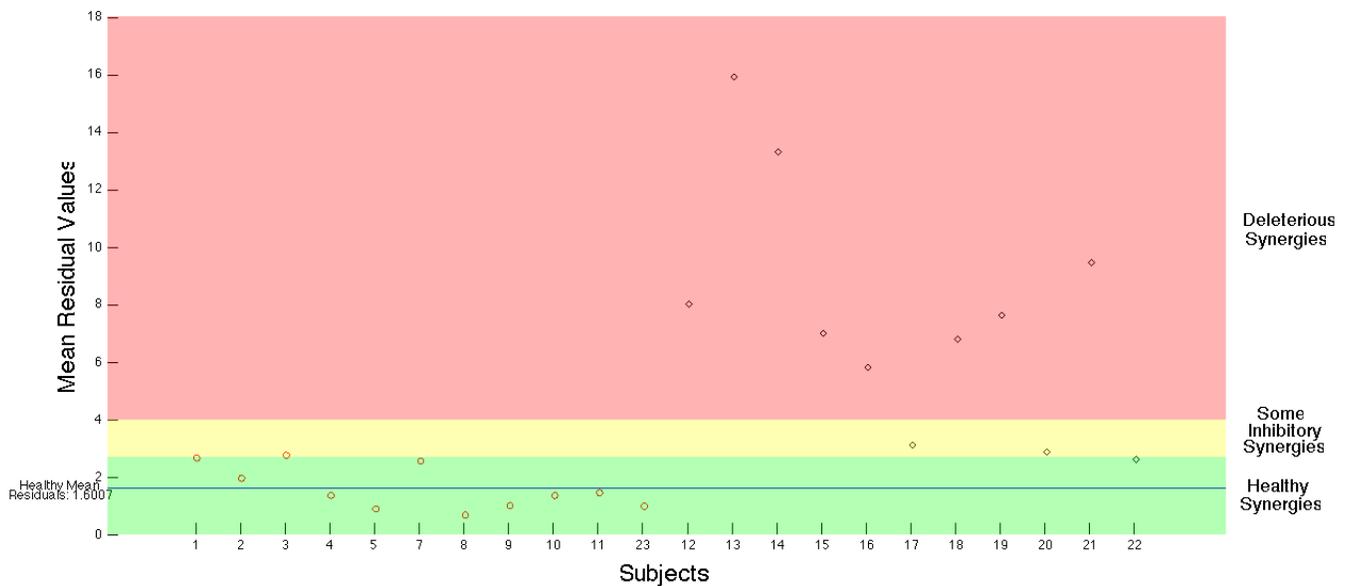


Fig. 14. This graph displays subjects' SM minus the gold standard healthy SM. The resulting residuals show healthy to deleterious synergies. Subjects 1, 3, 7, 22 are close on the boarder.

the matrix might allow for new types of therapy whereby the robot tracks progress and modifies movement training in a way that targets a patients individual needs.

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