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Assessment of Daily-Life Reaching Performance After Stroke

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Abstract—For an optimal guidance of the rehabilitation therapy of stroke patients in an in-home setting, objective, and patient-specific performance assessment of arm movements is needed. In this study, metrics of hand movement relative to the pelvis and the sternum were estimated in 13 stroke subjects using a full body ambulatory movement analysis system, including 17 inertial sensors integrated in a body-worn suit. Results were compared with the level of arm impairment evaluated with the upper extremity part of the Fugl-Meyer Assessment scale (uFMA). Metrics of arm movement performance of the affected side, including size of work area, maximum reaching distance and movement range in vertical direction, were evaluated during a simulated daily-life task. These metrics appeared to strongly correlate with uFMA scores. Using this body-worn sensor system, metrics of the performance of arm movements can easily be measured and evaluated while the subject is ambulating in a simulated daily-life setting. Suggested metrics can be used to objectively assess the performance of the arm movements over a longer period in a daily-life setting. Further development of the body-worn sensing system is needed before it can be unobtrusively used in a daily-life setting.

Keywords—Ambulatory assessment, Arm tasks, Fugl-Meyer.

ABBREVIATIONS

uFMA	Upper extremity part of the Fugl-Meyer assessment scale (0–66 points)
IMU	Inertial measurement unit

INTRODUCTION

Performance of several activities of daily living depends on proper arm function. Many stroke patients have a reduced ability to coordinate their arm movements. Intensive rehabilitation therapy is usually given to enhance recovery and studies have shown that this can increase arm motor recovery.[8,25] For an optimal guidance of the rehabilitation therapy, medical professionals need frequently measured and patient-specific information of arm function.[13] Currently, arm function of stroke patients is assessed according to the international classification of functioning.[10] In a clinical setting, this assessment is usually done on three levels. First, the assessment is performed on the level of body function, i.e., level of arm impairment (e.g., Fugl-Meyer Assessment[9]). Secondly and thirdly, the assessment is done on the level of activities and participation, i.e., assessment of prescribed arm tasks (e.g., action reached arm test,[17] stroke upper limb capacity scale[23]). However, it remains largely unknown whether the clinically assessed level of arm impairment, using for instance the uFMA, reflect the actual performance of arm movements in daily-life. Information of arm use in a daily-life setting will allow assessment of the transfer of learned arm movements to daily-life performance.[4]

Previous studies report methods for quantitative and qualitative assessment of upper arm movements in stroke subjects.[6–8,12,14,18,19,24,28] For instance, Kamper *et al.* report a decreasing active range of motion with increasing severity of impairment, in seated stroke subjects under the condition of restricted trunk motion.[12] Subramanian *et al.* suggest that movement quality metrics of trunk displacement and shoulder flexion are more sensitive in identifying upper extremity deficits than clinical scales.[24] Many of these kinematic studies have been performed in laboratory

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settings, with specialized laboratory-bound equipment.[7,8,12,14,18,19,24,28] However, for assessment of movement performance of the arm in a daily-life setting, a wearable system with a minimized impact on normal behavior is preferred.[1]

A feasible method for movement assessment in a daily-life setting is the use of inertial measurement units (IMUs). IMUs are small, unobtrusive and can easily be worn on the body. The main advantage of IMUs is that an external physical reference system is not required. This allows easy assessment of movements in a daily-life setting.[2,31] IMUs are already used for the evaluation of the upper extremity movements in terms of joint angles and end-point position, speed, acceleration and smoothness of the hands.[4,16,20,26,27] When using multiple inertial sensors, the orientation and movement of different parts of the body can be evaluated. Furthermore, with the addition of precisely measured body dimensions and a biomechanical model of the human body segments, relative positions of all instrumented extremities can be estimated using linked kinematic chain models.[22]

Long-term daily-life measurements may result in large amounts of kinematic data. Well-chosen metrics are needed to allow objective evaluation of arm movement performance in a daily-life setting and provide objective information about motor strategies associated with specific tasks.[4] These metrics may include maximum reaching distance, travelled path length and work area in multiple planes. Furthermore, hand position can be evaluated relative to the sternum as well as to the pelvis, to study compensatory trunk movement strategies. As a consequence of different (compensatory) strategies,[3] hand-sternum and hand-pelvis distances may vary differently between subjects.

The objective of this study is to evaluate metrics that describe daily-life arm movement performance in stroke subjects of both the affected and the unaffected arm in a simulated daily-life setting. These metrics were derived using a body-worn inertial sensing system and related to subject's scores of the frequently used upper extremity part of the Fugl-Meyer assessment scale in order to assess whether daily-life arm movement performance relates to clinically-assessed level of impairment.

MATERIALS AND METHODS

Participants

Seventeen stroke subjects were recruited from Roessingh rehabilitation hospital, located in Enschede, the Netherlands. Recruited subjects were between 35 and 75 years of age and had a hemiparesis as a result of a single unilateral stroke, diagnosed at least 6 months earlier. Furthermore, subjects had to be able to lift their affected arm against gravity from a relaxed vertical orientation onto a table directly in front of them while seated. Exclusion criteria were a medical history with more than one stroke, inability to understand questionnaires and inability to perform given instructions. The study protocol is a subset of a larger protocol approved by the local medical ethics committee. Each subject signed a written informed consent before participating.

Three subjects with severely affected lower extremity function were not able to complete the task without assistance due to instable walking patterns. The corresponding test results were excluded from the analysis. Data of one other subject was not fully recorded because of a broken cable during the session. Remaining were 13 subjects with an average age of 63.9 (SD ± 9.0) years, 2.3 (SD ± 1.8) years post stroke and of which eight are male. Subject specific information is reported in Table 1 and includes age, number of years post stroke, height, weight and dominant side.

Clinical Assessment of Stroke

Level of impairment of the affected side of the subject was assessed using the upper extremity part of the Fugl-Meyer Assessment Scale (uFMA). This scale ranges from zero to 66 points.[9] All assessments were performed by the same researcher with a background in technical medicine and adequate clinical expertise to perform the assessment.

Equipment

Kinematic data were recorded with the MVN Biomech motion capturing system (Xsens Technologies, Enschede, the Netherlands) at a frequency of 120 Hz.[22] To measure full body kinematics this system includes 17 IMUs positioned symmetrically on both sides, specifically at the feet, lower legs, upper legs, hands, lower arms, upper arms and shoulders. Additional sensors were positioned on sternum, sacrum and the head. To reduce movement artifacts sensors were mounted in plastic brackets strapped to the body and fixated to the skin using Velcro®. Sternum and shoulder sensors were attached using a small unobtrusive harness. Straps were tightened and wiring was tucked away behind clips, in the least obtrusive way. To check for any interfering straps or wires, subjects were asked to simply walk around and strapping and wiring were adjusted whenever necessary.

TABLE 1. General subject characteristics.

Subject ID[a]	Gender	Age[b]	Post stroke[b]	Dominant side	Affected side	uFMA[c]
s1	M	70	7.4	R	L	49
s2	M	69	4.0	R	L	43
s3	M	47	1.8	R	L	20
s4	M	73	2.4	R	R	54
s5	F	67	3.3	R	L	56
s6	M	65	1.3	R	L	53
s7	M	75	1.6	R	L	49
s8	M	52	1.6	R	L	36
s9	F	60	0.7	R	L	43
s10	F	71	1.4	R	R	63
s11	F	55	1.4	R	L	23
s12	F	56	1.6	R	L	59
s13	M	70	1.2	L	L	54

[a] Subject identification number.
[b] In years.
[c] Upper extremity part of the Fugl-Meyer assessment scale (0–66 points)[9].

Data of all sensors, 3D acceleration, 3D rotation velocity and 3D earth-magnetic field direction and Xsens' software MVN Studio Pro were used to estimate body segment orientation, relative segment position and full body 3D kinematics.[22] A reference video was recorded to verify estimated 3D kinematics.

Equipment Validation

Inherent to using IMUs is the presence of positional drift caused by integration of acceleration and angular velocity signals. This occurs after a few seconds of measuring.[11] More accurate estimates of relative positions of body segments can be obtained using prior knowledge of segment lengths and assuming a linked kinematic chain based on known joint constraints.[22]

To address this, the accuracy of the position estimates of the MVN Biomech system was first validated against an optical reference system (Vicon, Oxford Metrics, Oxford, United Kingdom). This experiment was performed on one healthy subject wearing both the IMUs and reflective markers positioned at the wrists, sternum and sacrum. While seated in front of a wooden table, performed several circular arm movements at three heights above the table. At each height 15 circular motions were performed with the left hand and 15 with the right hand. Movements were done in sequence and pairs of left and right arm motions were combined in single measurements. For all measurements the Euclidean distances from the base of the hand to the sternum and the base of the hand to the pelvis, were estimated using the MVN Biomech system and compared with the distances measured with the optical reference system. Mean and standard deviation of the differences between both measurements systems were evaluated.

Protocol

As a subset of a larger protocol, subjects were asked to perform a simulated in-home task. Arm movements were assessed while the subjects performed multiple daily-life activities. The task was repeated three times. The task started with the subjects seated on a wooden chair in front of a wooden table, with the chair completely pulled up to the table. Subjects were instructed to stand up from the chair, walk around the table, open, walk through and close a hinged door and walk to another table in the second room. On this table, two identical small solid tubes were placed upright, both having a diameter of 4.5 cm, a height of 12 cm and a weight of 500 g. Subjects were asked to grasp the first tube, lift and displace it to a marker on the other side of the table, a distance of 50 cm. Next, subjects were asked to grasp the second tube from the same table and return it to the starting table in the first room, passing through the same door. The height of both tables was 75 cm. The complete task was explained and demonstrated prior to the experiment and step-by-step instructions were also given while the subject was performing the task. A schematic overview of the task is presented in Fig. 1.

No explicit instructions concerning arm use were given to the subject while performing the simulated in-home task. Subjects were free to use their affected as well as non-affected arm in any way they preferred. The only objective given to the subjects was to complete the task. There was no time restriction imposed to fulfilling the task.

Data Analysis

The performance of reaching movements was derived from quantitative analysis of arm and trunk

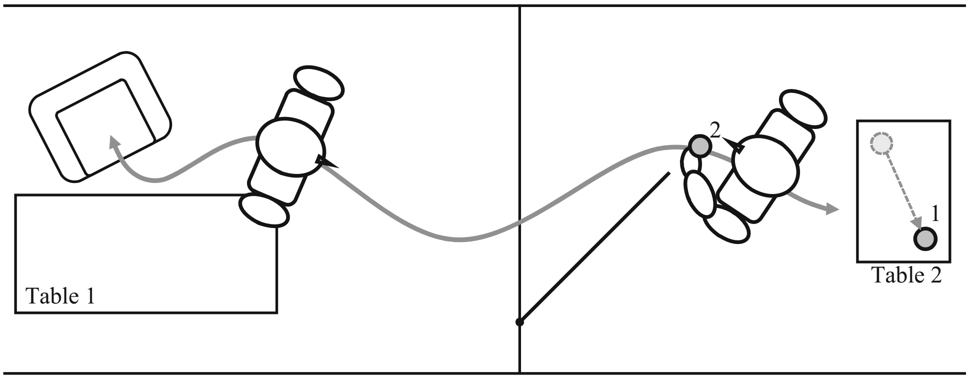

FIGURE 1. Schematic top-down overview of the simulated in-home task. Subjects start and finish at the first table (Table 1—left), walk along a hinged door, move the first tube (1) along the second table (Table 2—right) and take another tube (2) back to the first table.

movements. Kinematic data were processed offline by Xsens' MVN studio Pro and yielded relative segment positions and orientations. Subsequently, data was exported to and analyzed using Matlab® (MathWorks Inc., Natick, MA).

Kinematic data were expressed in a pelvis coordinate frame ψ^{p} as well in a sternum coordinate frame ψ^{s}. Of both coordinate frames the positive y direction was defined in posterior-anterior direction, positive z in vertical upwards direction, and x-axis perpendicular to the y- and y-axis in a right-handed fashion. Likewise, positions of the most proximal side of both hands, $P_{\mathrm{h}}^{\mathrm{p}}$ and $P_{\mathrm{h}}^{\mathrm{s}}$, were expressed in the coordinate frames of the pelvis and the sternum. For any hand this is:

$$P_{\mathrm{h}}^{\mathrm{p}} = R^{\mathrm{gp}\prime} * (P_{\mathrm{h}}^{\mathrm{g}} - P_{\mathrm{p}}^{\mathrm{g}}),$$

$$P_{\mathrm{h}}^{\mathrm{s}} = R^{\mathrm{gs}\prime} * (P_{\mathrm{h}}^{\mathrm{g}} - P_{\mathrm{s}}^{\mathrm{g}}),$$

where $P_{\mathrm{h}}^{\mathrm{g}}$ is the position of the proximal side of the hand in the global coordinate frame, $P_{\mathrm{p}}^{\mathrm{g}}$ and $P_{\mathrm{s}}^{\mathrm{g}}$ are the positions of the pelvis and the sternum in the global coordinate frame, and $R^{\mathrm{gp}\prime}$ and $R^{\mathrm{gs}\prime}$ are the transposed rotation matrices expressing the pelvis and the sternum in the global coordinate frame.

Four metrics were used for evaluation of the performance of arm movements during the complete task. The first metric is the work area of each hand, estimated from the hand positions during the simulated in-home task and expressed in both the pelvis and sternum coordinate frames. More specifically, a Delaunay triangulation method was used, to create a two dimensional envelope around all positions of a hand in both the transversal and the sagittal plane. The areas of the envelopes were used as the estimated work areas. Secondly, to quantitatively assess hand movements in three-dimensions, the lengths of the 3D trajectories of both hands were evaluated. These trajectory lengths were estimated using the summation of Euclidean distances between consecutive positions of each hand expressed in the pelvis and the sternum coordinate frames. Thirdly, to qualitatively assess performance of arm reaching, largest reached distances between hand and pelvis as well as between hand and sternum were determined after projection of the hand movements in the transversal plane. Finally, the range of height differences between each hand and the pelvis and each hand and the sternum were estimated.

Statistical Analysis

Results were averaged per subject and corrected for body height. Linear regression analysis was performed to estimate correlation of determination values between described metrics for both the affected and non-affected arms and uFMA scores.

RESULTS

Equipment Validation

The 45 validation measurements were successfully recorded using both the MVN Biomech system and the optical reference system. The differences in distances estimated using both systems vary across all measurements and increase with hand-sternum distances. Averaged mean absolute differences of estimated distances evaluated over all measurements is 14 mm (SD ± 13 mm) for hand-sternum and 35 mm (SD ± 34 mm) for hand-pelvis. Over all measurements the mean of the largest absolute differences between both systems is 58 mm (SD ± 20 mm) for hand-sternum distance and 141 mm (SD ± 32 mm) for hand-pelvis distance.

Simulated In-Home Task

All kinematic data were recorded without loss of data. Figure 2 shows typical hand position data with

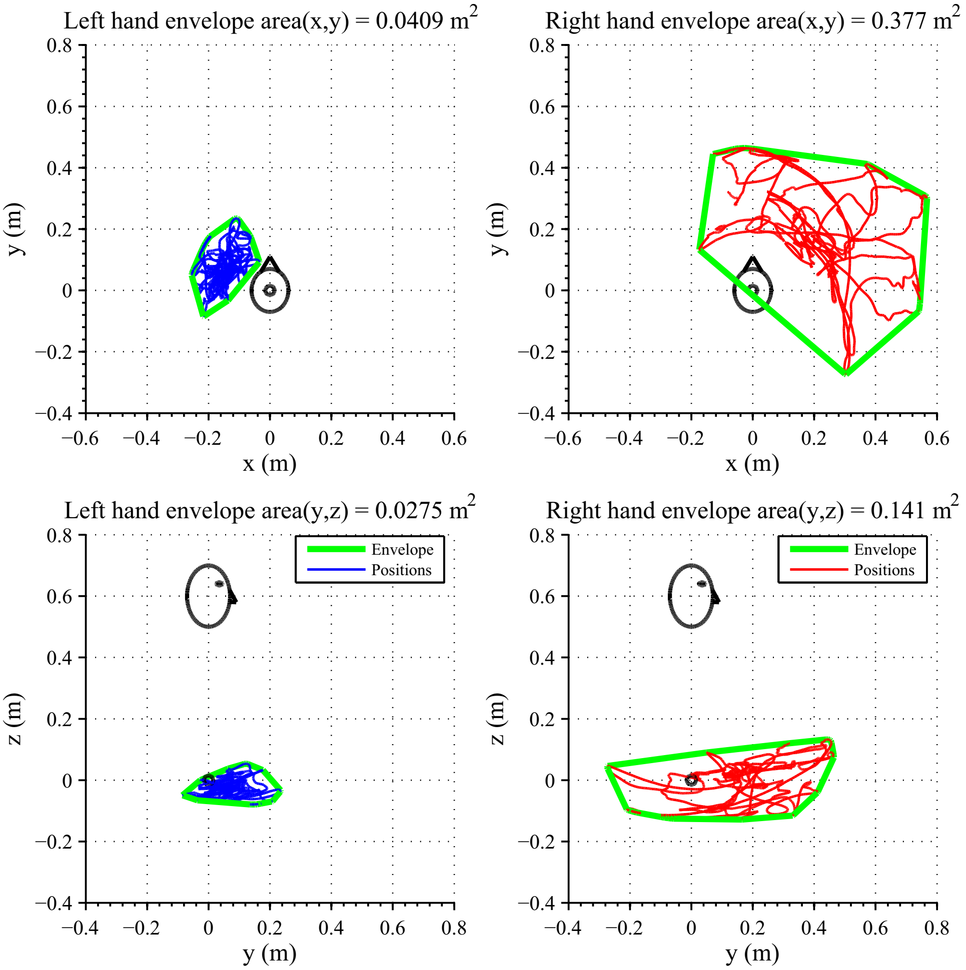

FIGURE 2. Upper graphs- top-down view: transverse plane (*xy*-plane). Lower graphs—side view: sagittal plane (*yz*-plane). All showing arm positions relative to the pelvis (origin of the graph) during the simulated in-home task and corresponding envelope. Position data of a 28 s measurement. Subject number 3, uFMA = 20 out of 66.

respect to the pelvis for a single subject (subject 3, uFMA score of 20 out of 66) performing the simulated in-home task. The thin traces show the trajectories projected on the transversal plane (xy-plane) as well as on the sagittal plane (yz-plane) of both hands relative to the position of the pelvis. The thicker green envelopes around the trajectories represent the overall largest reached distances in all directions in the transversal and the sagittal planes, while performing the simulated in-home task.

Table 2 specifies the correlation of determination values for all four metrics evaluating hand positions relative to the pelvis and to the sternum for both the affected and unaffected side. All corresponding correlation coefficients were found to be positive, except for the largest reaching distance of the non-affected side, relative to the sternum in the transversal plane. Significant correlations with the uFMA scores were only found in the metrics evaluating hand movements of the affected side relative to the pelvis as well as relative to the sternum. The first correlating metric is the work area of the affected arm for movements in the transversal plane relative to the pelvis and the sternum (resp. $r = 0.84$, $p < 0.001$ and $r = 0.70$, $p < 0.01$), as well as in the sagittal plane relative to the pelvis and the sternum (resp. $r = 0.84$, $p < 0.001$ and $r = 0.79$, $p < 0.01$). Second correlating metric is the maximum reached distance in transversal plane relative to the pelvis and the sternum (resp. $r = 0.88$, $p < 0.001$ and $r = 0.82$, $p < 0.001$). The third correlating metric is the range in vertical hand elevation relative to the pelvis and the sternum (resp. $r = 0.69$, $p < 0.05$ and $r = 0.76$, $p < 0.01$). No significant correlations were found for the metric evaluating path length of the hand of the affected side relative to the pelvis as well as relative to the sternum. Figure 3 shows the results per patient of the three highest correlating metrics relative to their uFMA scores.

TABLE 2. Correlation of determination values (R^2) between metrics and uFMA scores.

		Relative to pelvis		Relative to sternum	
	Plane	A	NA	A	NA
Work area	*XY*	0.70^{***}	0.03	0.49^{**}	0.06
	YZ	0.70^{***}	0.08	0.62^{**}	0.17
Length of hand trajectories	*XYZ*	0.23	0.01	0.20	0.05
Maximum reaching	*XY*	0.77^{***}	0.07	0.68^{***}	0.14[a]
Range of vertical hand elevation	*Z*	0.47^{*}	0.21	0.58^{**}	0.25

A, Affected side; NA, Non-affected side; *XY*-plane, transversal plane; YZ-plane, sagittal plane; XYZ-plane, three-dimensional.

* p value < 0.05, $^{**}p$ value < 0.01, $^{***}p$ value < 0.001.

[a] Corresponding correlation coefficient is negative. Results and corresponding linear models of underlined values are shown in Fig. 3.

DISCUSSION

The objective of this study was to evaluate metrics which describe daily-life arm movement performance in stroke subjects, using a body-worn inertial motion capture system. These metrics, estimated for a simulated in-home task, appeared to be related to subject's uFMA scores, which express level of arm impairment. Significant correlations were found between uFMA scores and movement performance metrics estimated for the affected side in both the coordinate frames of the pelvis as well as the sternum. The uFMA scores appeared to significantly correlate with (1) the work area of the affected arm in the transversal and sagittal planes, (2) maximum reaching distance and (3) the range of vertical hand elevation. High correlation of determination values between these metrics and the uFMA scores show that the variance of the metrics is highly predictable from the uFMA scores. Corresponding correlations coefficients show strong positive relationships between these metrics and uFMA scores. These relationships show that stroke subjects with a higher uFMA score, that is a lower level of arm impairment, move their affected arm during a simulated in-home task over a larger area, a larger distance and a larger range of hand elevations than subjects with lower uFMA scores, representing a higher level of arm impairment. Since spasticity is a component of the uFMA this could at least in part account for the correlation in the data.[3,5,7,19] Similar correlations were reported in stroke subjects performing more prescribed tasks, between uFMA scores and metrics describing kinematics of stroke subjects.[7,8,12,14,19,24,28]

Strikingly, no relationships were found between the uFMA scores and any of the arm movement metrics evaluated for the non-affected arm. Such relationships could have been expected when assuming that severely affected subjects would compensate for the reduced movements of their affected side by enlarging the work area at their non-affected side. The absence of such relationships might be explained twofold. First, arm preference might have caused even less affected subjects to move their non-affected arm more. The preferred arm is the non-affected arm in 10 out of the 13 subjects that participated in the current study (Table 1). Secondly, a subject with a higher level of arm impairment could have an increased rotation of the pelvis in the transversal plane while completing the task, such that the required actions can be performed in the working area of the non-affected arm. This compensation strategy would not result in an increased reaching area or distance of the non-affected arm.

Hand positions were evaluated relative to the sternum as well as relative to the pelvis. Differences between hand-sternum distances and hand-pelvis distances could have been expected as a result of compensatory trunk movements. Stroke subjects with a higher level of arm impairment will show less shoulder flexion and may compensate during reaching by trunk flexion.[24] Such compensatory movements of the trunk would increase hand-pelvis but not hand-sternum distance. This would result in higher correlations with uFMA scores for metrics describing movements of the hand relative to the sternum than relative to the pelvis. However, this was only found for the metric describing the range of vertical hand elevation. Therefore, our results do not indicate compensatory trunk movements during reaching in this simulated daily-life task.

To evaluate subject's arm movements in a simulated daily-life setting, no explicit instructions concerning arm use were given to the subject. As a consequence, subjects could use different strategies to complete the prescribed task. For instance, subjects walked through the same door in two directions and even though the hinge is on different sides while opening and closing the door, more affected subjects opened and closed the hinged door in both directions with their non-affected side while several of the less affected subjects used both arms. Another example of different strategies is the way subjects moved a tube from one room to the other. Some of the subjects kept the tube in the hand of their non-affected side at all time, while others moved the

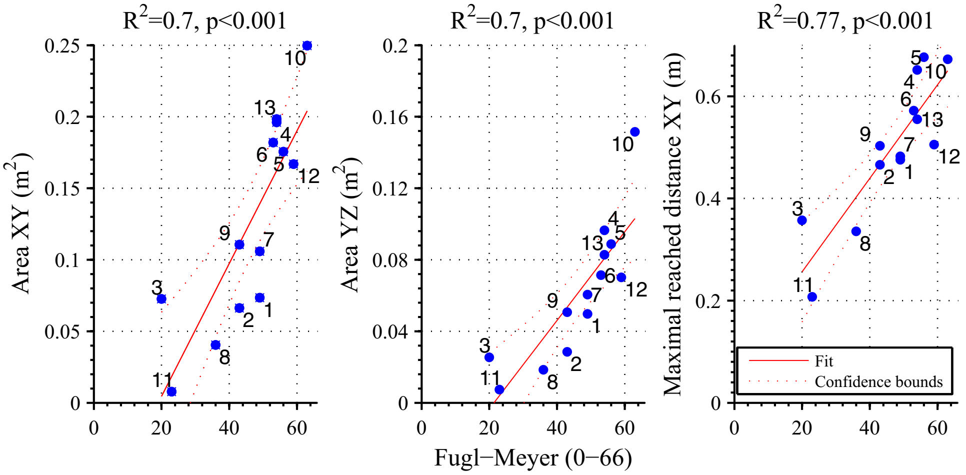

FIGURE 3. Three graphs show relation between uFMA scores and three metrics with the highest correlation of determination values for the simulated in-home task. First metric, mean area of the envelopes around movements of the affected arm in the transversal plane (*xy*-plane), second metric, area around movements of the affected arm in the sagittal plane (*yz*-plane) and third metric is the maximal reached distance between pelvis and hand in the transversal plane (*xy*-plane).

tube from their non-affected to their affected hand before opening the door with their non-affected side. Furthermore, a different impairment level of the hand can influence strategies. Using the MVN Biomech system, actual grasping cannot be detected and the way of grasping cannot be evaluated. Therefore, no distinction can be made between subjects who are unable to and those who do not choose to use their affected hand for grasping. However, subjects who have a lower uFMA score, especially for the hand evaluation parts, can be expected to apply alternative reaching and grasping strategies, avoiding using their affected arm and hand.[3] Positive correlations of the affected arm metrics with uFMA that were found may, therefore, be related to differences in applied reaching and grasping strategies. It should be noted that the considered simulated in-home task is of limited difficulty and may have been completed single-handedly. The difficulty of the selected task may, therefore, have been of influence on the results of the metrics. Bimanual tasks, tasks with different object sizes or evaluating arm movements over a longer period may show different results.

Validation measurements, performed in one healthy subject, show larger differences at larger reaching distances between the MVN Biomech system and the optical reference system. Differences are not random, but predictably related to reaching distance. These differences may be caused by incomplete registration of shoulder protraction and retraction and trunk movements by the MVN Biomech system. The shoulders and the back are not rigid body segments, therefore movements in these segments cannot completely be registered with the limited number of IMUs applied. Accuracy could be increased by using for instance additional sensing with goniometers on the spine and shoulder[15] or alternatively by fusing magnetic and inertial sensing.[21] Despite the deviations in distance estimation, assessed arm reaching appeared to be significantly correlated with uFMA in stroke subjects.

Several limitations in the present work should be acknowledged. First, the task is performed in a simulated daily-life setting; this setting will be different from the subject's daily-life setting. The subject might be unused to the setting and may apply different or non-optimal movement strategies compared with a real in-home setting. Secondly, no healthy control data of the simulated in-home task has been measured. Therefore, it remains unknown how much movement normally exists while completing the simulated in-home task. The best available control data in our study are the movements of the less affected subjects performing the simulated in-home task. Our study demonstrates that these subjects use their affected arm more extensively than the more impaired subjects. Thirdly, motor performance varies over time within a single individual, as well as across different individuals performing the same task in different ways. We calculated the mean of three trials for each metric. This limited number of trials may have influenced the outcome. However, it should be noted that there is no consensus about the optimal number of repeated trials when evaluating reaching tasks in people with hemiparesis after stroke.[30] Fourthly, while the uFMA also includes the evaluation of reflex actions and grasp types, these types of movements cannot be assessed using the MVN Biomech system. Finally, the straps, the large number of sensors and sensor cables may have influenced the movements of subjects while performing the simulated in-home task. Further developments of the body-worn sensing system are necessary before it can be used unobtrusively for evaluation of improvement or deterioration of arm movements over longer periods of time during daily life.[29] Such a system must have small-embedded sensors, not be directly visible for others, not be stigmatizing and have no influence on normal daily-life behavior.[1]

Many studies have described methods that could potentially be used to evaluate arm movement in daily-life settings.[2,12,18,19,24,27,28,30] These methods often describe arm movements in terms of acceleration, velocity or smoothness of movement of a single segment. Our proposed method combines IMU measurements on several segments for estimating metrics describing end-point hand kinematics relative to the trunk. These metrics, which evaluate relative position data, are easy to collect and may be more easily interpreted. In addition to the proposed metrics, qualifying movement performance of the arm in a daily-life setting, other metrics could be evaluated. For instance, metrics which relate orientation of the upper and lower arm to describe independent joint control during functional tasks[3,5,6,18,19] or smoothness of movements.[3,12,19,28,30] An adequate activity monitor and classifier could give context to performed arm movements, which will allow the evaluation of arm movements using the suggested metrics on a functional level.

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