(Online)

Standardized measurement of quality of upper limb movement after stroke: Consensus-based core recommendations from the Second Stroke Recovery and Rehabilitation Roundtable

Kwakkel G.* (a,b,c,). Orcid ID: https://orcid.org/0000-0002-4041-4043
[a] Amsterdam UMC, location VU Medical Centre, Department of Rehabilitation Medicine, Amsterdam Movement Sciences, Amsterdam Neuroscience, de Boelelaan 1117, Amsterdam, The Netherlands.
[b] Dept Neurorehabilitation, Rehabilitation Centre Reade, Amsterdam, The Netherlands.
[c] Department of Physical Therapy and Human Movement Sciences, North Western University, Chicago, Il, United states.

Van Wegen EEH (a,b) Orcid ID: https://orcid.org/0000-0002-7920-9995
[a] Amsterdam UMC, Vrije Universiteit Amsterdam, Department of Rehabilitation Medicine, Amsterdam Movement Sciences, Amsterdam Neuroscience, de Boelelaan 1117, Amsterdam, The Netherlands.
[b] Dept Neurorehabilitation, Rehabilitation Centre Reade, Amsterdam, The Netherlands.

Burridge JH. (a) Orcid ID: https://orcid.org/0000-0003-3497-6725
[a] School of Health Sciences, Faculty of Environmental and Life Sciences , University of Southampton
Southampton, UK SO17 1BJ.

Winstein CJ. (a,b) ORCID ID: https://orcid.org/0000-0001-9789-4626
[a] University of Southern California, Division of Biokinesiology and Physical Therapy, at the Herman Ostrow School of Dentistry, Health Sciences Campus, Los Angeles, CA, USA
[b] University of Southern California, Department of Neurology, Keck School of Medicine, Health Sciences Campus, Los Angeles, CA, USA

Van Dokkum LEH. (a) Orcid ID: https://orcid.org/0000-0002-3278-7456
[a] I2FH, institue d'imagerie fonctionelle humaine, Montpellier University Hospital Gui de Chauliac, France.

Alt Murphy M. (a) Orcid ID: ID: https://orcid.org/0000-0002-3192-7787
[a] Department of Clinical Neuroscience, Rehabilitation Medicine, Institute of Neuroscience and Physiology, Sahlgrenska Academy, University of Gothenburg, Sweden

Levin MF. (a, b) Orcid ID: ID: https://orcid.org/0000-0002-8965-7484
[a] School of Physical and Occupational Therapy, Faculty of Medicine, McGill University, Montreal, Quebec, Canada
[b] Center for Interdisciplinary Research in Rehabilitation, Montreal, Quebec, Canada

Krakauer JW (a, b, c) Orcid ID: https://orcid.org/0000-0002-4316-1846
[a] Department of [a]Neurology,
[b]Neuroscience, and [c]Physical Medicine & Rehabilitation.
The Johns Hopkins University School of Medicine, USA

* **Corresponding author: Gert Kwakkel**
Department of Rehabilitation Medicine,
Amsterdam UMC, location VUmc, Amsterdam, de Boelelaan 1117,
1081 HV Amsterdam,
The Netherlands.
E-mail: G.Kwakkel@amsterdamumc.nl

On behalf of the ADVISORY group*.

Lang, Catherine E. (a)
ORCID ID: https://orcid.org/0000-0002-7120-0136
[a] Physical Therapy, Occupational Therapy, Neurology Washington University School of Medicine
St. Louis, MO USA

Keller, Thierry (a)
ORCID ID: https://orcid.org/0000-0003-4000-958X
[a] Neurorehabilitation Department, Health Division, Tecnalia Research & Innovation, San Sebastian, Spain.

Kitago Tomoko (a)
ORCID ID: https://orcid.org/0000-0003-0222-6698
[a]Burke Neurological Institute and [b]Department of Neurology, Weill Cornell Medicine, USA.

Nordin, Nurdiana (a)
ORCID ID: https://orcid.org/0000-0003-4368-6922
[a] Centre for Robotics and Industrial Automation, Fakulti Kejuruteraan Elektrik, Universiti Teknikal Malaysia Melaka, Malaysia.

Pomeroy, Valerie (a)
ORCID ID: https://orcid.org/0000-0003-4487-823X
[a] School of Health Sciences, University of East Anglia, Norwich, NR4 &TJ, United Kingdom.

Veerbeek, Janne M. (a)
ORCID ID: https://orcid.org/0000-0002-6337-6780
[a] Division of Vascular Neurology and Neurorehabilitation, Department of Neurology, University Hospital Zurich, University of Zurich, Switzerland; cereneo, Center for Neurology and Rehabilitation, Vitznau, Switzerland

van Wijck, Frederike,
ORCID ID: https://orcid.org/0000-0003-0855-799X
[a] School of Health and Life Sciences, Glasgow Caledonian University Cowcaddens Road Glasgow, UK.

Panel 1: Definitions.

1. **The International Classification of Functioning, Disability and Health** (ICF) The International Classification of Functioning, Disability and Health, known more commonly as ICF, is a classification of health and health-related domains. As the functioning and disability of an individual occurs in a context, ICF also includes a list of environmental factors. https://www.who.int/classifications/icf/en/

2. **Motor control:**
A field of natural science studying behavioural properties and neural mechanisms of biological movement. More specifically, good motor control leads to "The proper execution of a movement with a particular effector in a specific task context[1]. Execution ideally should be measured using quantitative analyses of endpoint and joint kinematics, and when appropriate, dynamics and EMG.

3. **Quality of movement:** Movement quality in this document is operationally defined through a direct comparison of a patient's motor execution of a task or action to a reference population of non-disabled age-matched control subjects. The closer the movement matches those seen in controls, the better the quality of their movement.

4. **Behavioral recovery**: Actions that reflect a return towards or full restitution to pre-morbid movement execution patterns[2].

5. **Behavioral compensation**:
Completing a task using alternative effectors, joints or muscle patterns. That is to say in a manner that is qualitatively different than that of non-disabled, age-matched controls[3].

6. **End-effector**:
Defined as a body part, such as a hand or foot, that interacts with an object or the environment[3].

7. '**Performance assays':** Tests that quantify aspects of rudimentary motor control performance more or less isolated from functional task contexts. For example, finger individuation or force production in the biceps muscle. The assumption is that these assays best capture the true upper bound of the degree of true neurological recovery. This includes the concept that performance assays are tests that quantify motor control deficits that underlie disruptions in functional movements. With that, performance assays are defined at the body structure/body function level of the ICF.

8 '**Functional tasks**': Tasks require the assembly of rudimentary motor execution abilities into functional movements. These tasks can be accomplished either through behavioural restitution or compensation or a combination of both. With that, functional tasks are defined at the activity level of the ICF.

9. **Inertial Measurement Units** (IMUs): Electronic devices that measure and provide a body's specific acceleration, angular rate of a body segment at its attachment point. In some cases includes the magnetic field surrounding the body, using a combination of accelerometers and gyroscopes, and in some cases also magnetometers[4].

10. **Hi-fidelity optical systems:** Systems that use optoelectronic techniques, where the kinematic measurement may be made in two dimensions (i.e., 2D) or three dimensions (i.e., 3D). For 3D motion capture multiple high-speed cameras are used. The cameras either capture reflections from passive markers placed on the body or transmit the movement data from active markers based on infrared emitting diodes. These systems are considered as 'gold standard' for the acquisition of kinematic data and are subject to specific calibration, and standardization procedures (e.g., marker sets) to maintain data quality.

11. **Movement trajectory:** Kinematic representation of the movement path executed by a participant.

12. **The "metric" task force:** The metric task force is a group of scientists with expertise in the movement sciences including biomechanics, neuroscience, motor control and motor learning in the domain of stroke recovery that collaborated in this consensus meeting as a part of the Stroke Recovery and Rehabilitation Roundtable group held in Montreal, October 21st and 22nd , 2018.

Panel references:

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Appendix A: Recommended trajectory control measures for performance assays in 2D.

1. Endpoint trajectory smoothness, defined as the number of peaks in the endpoint marker tangential velocity profile from movement onset to offset[1];

2. Endpoint straightness, defined as the index of curvature (IC) or the ratio between the length of the trajectory of the endpoint marker and the length of a straight line between the initial and final targets.

3. Endpoint error, defined as the 2D Root Mean Square Error (RMSE) between the final endpoint marker and target position.

4. Movement speed, defined as the value of the peak tangential velocity of the endpoint marker or the movement time from movement onset to offset.

5. Range of joint movement used to perform the task (i.e., joint angles: shoulder, elbow, wrist, fingers).

Additional recommended performance assays:

1. Reaction time, defined as the time between the beginning of the 'go' signal and the beginning of the arm movement.

2. Arm-hand postural stability: 2 measures can be used: 1) the amount and variability of endpoint marker oscillations at the start and end of the reach; 2) response to perturbation of the forearm or hand, imposed by a torque motor for example, when the patient is instructed to maintain their arm in the initial position. Postural stability can also be assessed by evaluating the responses to perturbation of the endpoint in the final position. The amplitude and variability of the endpoint deviation from the intended initial or final position is measured.

References:

[1]Adamovich SV, Archambault PS, Ghafouri M, Levin MF, Poizner H, Feldman AG. Hand trajectory invariance in reaching movements involving the trunk. *Exp Brain Res*. 2001;138:288-303.

Appendix B. Test protocol, equipment and metrics recommended for the 3D movement tasks at activity level [1]. See also online videoclip: (https://www.jove.com/video/57228/)

- Adjustable table and chair height so that hips and knees are at 90 degrees, and elbow at 90 degrees when the hand is resting on the edge of the table, without shoulder elevation. The back is against the chair's backrest, arm in neutral adducted position, and the palm of the hand resting at the table with wrist aligned to the edge of the table (Figure 3 A and B).

- The drinking cup (hard-plastic cup, diameter 6-7 cm, height 9-10 cm) with 100 mL of water is placed at standardized position in the midline of the body: 30 cm from the table edge which corresponds to a distance at wrist level when the arm is fully extended. The position of cup corresponds to a natural location of a cup in real-life table setting.

- Markers are placed on skeletal landmarks on the tested hand, forearm, upper arm, shoulders, thorax and face according to the protocol for the drinking task. Reference markers may be needed on the object (drinking cup) for calculation of movement phases.

- The task should be performed at least 15 times, after familiarization, with enough rest between each trial (10-30 seconds). Participants need to receive sufficient rest between the movements to minimise the risk of fatigue that might affect the quality of movement. In case of fatigue, the requested movement can be executed in blocks of 3 or 5 with sufficient rest periods between the trials.

- The unimanual drinking task should be executed with the impaired as well as with the less impaired arm.

Equipment for the functional tasks
An optical motion capture system including 3-6 (5-6 is optimal) high-speed cameras is currently seen as the golden standard and would be the first choice. Electromagnetic systems can be used, with a minimal sample frequency of 60 Hz and standardized calibration procedures. IMUs are currently not recommended as first choice for measurement of quality of movement in defined movement tasks.

Metrics for the drinking task:
End-point kinematics (marker on the hand):

- **Movement time** defined for the entire task and/or separate movement phases (reach-to-grasp, transport to mouth, drinking, transport back, return hand back to initial position). Movement time does not directly address the quality of movement but is strongly correlated to the movement smoothness and therefore provides an indirect measure of movement quality[2].
- **Movement smoothness:** Movement smoothness is a quality measure of a movement related to the continuity of a movement, independent on amplitude and duration of the movement [2, 3]. Unfortunately, there is no consensus how to measure the smoothness of movements and many of these measures are unreliable or invalid[3,4]. In the literature, more than 25 different algorithms have been suggested for measuring quality of movement [3]. Smoothness can be classified into a frequency or time domain. In the frequency domain, the smoothness metric can be classified in the group of 'Frequency metrics', whereas in the time domain, the metric can be classified into the: 1) 'Trajectory metrics', 2) 'Velocity metrics', 3) 'Acceleration metrics'

or 4) 'Jerk metrics'. Only trajectory, velocity and jerk metrics of functional 3D tasks have been validated in stroke populations [5].

Smoothness in the velocity domain can be calculated as number of movement units (NMU) in the tangential velocity profile. One movement unit can be defined as a difference between a local minimum and next maximum velocity value that exceeds the amplitude limit of 20 mm/s, if the time between 2 subsequent peaks is at least 150 ms. A smooth reach results in a bell shape velocity profile with 1 predominant velocity peak. Multiple peaks in velocity profile signify repetitive acceleration and deceleration during reaching indicating an unsmooth and less efficient movement. Since there are 4 movement phases (drinking excluded) in the drinking task, the minimum number of movement units is 4 (for reference values see Appendix C).

- **Peak velocity** of reach phase
- **Time to peak velocity (%)** of reach phase

Joint and segment kinematics

- **Trunk displacement** in forward direction (displacement data in cm or angle in degrees)
- **Joint angles** (degrees): maximum elbow extension during reaching phase (occurs in the end of reach), maximum arm abduction (or flexion) during drinking phase (reflects the synergy dependent compensatory movement pattern)
- **Peak angular velocity of elbow extension** during reach (°/s)

The recommended minimal change

Minimum clinically important change in absolute values for drinking task corresponding to at least 6 points improvement in ARAT during the first 3 months post stroke (Alt Murphy 2013):

- Total movement time: 2,4 seconds
- Smoothness (NMU) in 4 movement phases: 3 units
- Trunk displacement: 2 cm

In relative terms, a clinically significant change (improvement or decline) in recommended metrics has shown to be approximately 10%, and a clinically important change has shown to be approximately 15% [6,7].

Other metrics to consider for functional tasks (metric properties not (yet) established for the drinking task) [8,9].

- End-point smoothness: jerk metrics (normalized jerk)
- End-point trajectory: length or curvature, hand-path ratio as indirect measure of coordination
- Joint coordination: measures of temporal coordination during reach (2D inter-joint cross correlation between elbow and shoulder joint movements) and spatial coordination (angle-angle diagram between elbow and shoulder joint movements)[10].

References:

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Appendix C. Reference values for movement performance in drinking task in non-disabled controls.

	Age 25-50 n=22			Age 51-65 n=20			Age 66-85 n=42			All ages n=84		
	11 woman, 11 men			10 woman, 10 men			21 woman, 21 men			42 woman, 42 men		
	Mean	SD	95%CI	Mean	SD	95%CI	Mean	SD	95%CI	Mean	SD	95%CI
NON-DOMINANT ARM												
End-point kinematics												
Total movement time, s	5.73	0.76	5.40;6,07	6.33	0.77	5.97;6.69	6.60	1.06	6.20:6.87	6.28	0.98	6.07;6.49
Movement units (reach, forward transport), n	2.06	0.13	2.00; 2.12	2.22	0.38	2.04;2.40	2.35	0.42	2.21;2.48	2.24	0.37	2.16;2.32
Movement units (back transport, return)	3.51	0.87	3.13;3.90	4.03	0.81	3.65;4.40	3.93	1.05	3.61;4.26	3.85	0.96	3.64;4.05
Total movement units, n	5.64	0.92	5.23;6.04	6.18	0.87	5.78;6.59	6.11	1.08	5.77;6.44	6.00	1.00	5.78;6.22
Peak hand velocity in reach, mm/s	663	98.6	619;707	611	81.9	572;649	635	112	600;670	637	103	614;659
Time to peak velocity in reach, %	0.46	0.06	0.43;0.48	0.45	0.06	0.43;0.48	0.43	0.08	0.41;0.46	0.44	0.07	0.43;0.46
Joint and segment kinematics												
Peak elbow angular velocity in reach, °/s	123	29.7	110;136	112	26.7	99.0;124	107	27.0	98.4;115	112	28.1	106;118
Arm abduction in drinking, °	26.9	12.1	21.5;32.3	27.7	9.9	23.0;32.3	29.1	9.8	25.9;32.0	28.1	10.4	25.9;30.4
Elbow extension in reach-to-grasp, °	55.6	7.6	52.2;58.9	52.6	8.8	48.5;56.7	54.0	7.4	51.7:56.3	54.0	7.7	52.4;55.8
Trunk Displacement, mm	28.2	14.3	21.9;34.5	35.1	20.3	25.6;44.6	33.5	14.3	29.1;38.0	32.5	16.0	29.1;36.0
DOMINANT ARM												
End-point kinematics												
Total movement time, s	5.57	0.76	5.23;5.90	6.31	0.77	5.96;6.67	6.41	1.01	6.10;6.73	6.17	0.96	5.96;6.37
Movement units (reach, transport to mouth)	2.06	0.17	1.99;2.13	2.12	0.22	2.01;2.22	2.21	0.31	2.11;2.31	2.15	0.27	2.09;2.21
Movement units (transport back, return)	3.15	0.97	2.72;3.58	3.77	1.00	3.30;4.24	3.55	0.84	3.29;3.82	3.50	0.93	3.30;3.70
Total movement units, n	5.23	1.07	4.75;5.70	5.89	1.03	5.41;6.37	5.79	0.85	5.53;6.06	5.67	0.98	5.45;5.88
Peak hand velocity in reach, mm/s	703	113	653;753	634	95.8	589;678	644	134	603;686	657	122	631:684
Time to peak velocity in reach, %	0.45	0.05	0.43;0.46	0.44	0.05	0.42;0.47	0.43	0.07	0.41;0.45	0.44	0.06	0.43;0.45
Joint and segment kinematics												
Peak elbow angular velocity in reach, °/s	115	27.8	103;128	108	25.6	96.3;120	101	25.5	92.9;109	106	26.5	101;112
Arm abduction in drinking, °	34.3	10.5	29.6;39.0	31.8	10.1	27.1;36.5	34.5	11.0	31.1;37.9	33.8	10.6	31.5;36.1
Elbow extension in reach-to-grasp, °	57.8	7.3	54.6;61.0	54.2	8.4	50.2;58.1	56.8	7.2	54.5;59.0	56.4	7.5	54.8;58.1
Trunk Displacement, mm	25.7	12.6	20.1;31.3	32.9	18.0	24.5;41.4	31.2	14.9	26.5;35.9	30.2	15.3	26.9;33.5
Mean age, years	40.7	5.5	38.3;43.1	57.2	4.9	54.9;59.5	71.8	4.9	70.3;73.4	60.2	14.0	57.1;63.2
Mean height, cm	171	8.79	167;175	173	9.13	169;178	173	8.96	170;176	173	8.87	171;175
Mean weight, kg	61.6	17.0	54.0;69.1	67.2	16.8	59.3;75:0	72.8	14.5	68.3;77.8	68.5	16.2	65.0;72.1