Video Article

Kinematic Analysis Using 3D Motion Capture of Drinking Task in People With and Without Upper-extremity Impairments

Margit Alt Murphy[1,3], Steve Murphy[2], Hanna C. Persson[1,3], Ulla-Britt Bergström[3], Katharina Stibrant Sunnerhagen[1]

[1]Institution of Neuroscience and Physiology, Rehabilitation Medicine, Sahlgrenska Academy, University of Gothenburg

[2]Securesoft Sweden

[3]Departement of Occupational Therapy and Physiotherapy, Sahlgrenska University Hospital

Correspondence to: Margit Alt Murphy at Margit.Alt-Murphy@neuro.gu.se

URL: https://www.jove.com/video/57228
DOI: doi:10.3791/57228

Keywords: Neuroscience, Issue 133, Kinematics, task performance and analysis, outcome assessment, upper extremity movement, activities of daily living, stroke

Date Published: 3/28/2018

Citation: Alt Murphy, M., Murphy, S., Persson, H.C., Bergström, U.B., Sunnerhagen, K.S. Kinematic Analysis Using 3D Motion Capture of Drinking Task in People With and Without Upper-extremity Impairments. *J. Vis. Exp.* (133), e57228, doi:10.3791/57228 (2018).

Abstract

Kinematic analysis is a powerful method for objective assessment of upper extremity movements in a three-dimensional (3D) space. Three-dimensional motion capture with an optoelectronic camera system is considered as golden standard for kinematic movement analysis and is increasingly used as outcome measure to evaluate the movement performance and quality after an injury or disease involving upper extremity movements. This article describes a standardized protocol for kinematic analysis of drinking task applied in individuals with upper extremity impairments after stroke. The drinking task incorporates reaching, grasping and lifting a cup from a table to take a drink, placing the cup back, and moving the hand back to the edge of the table. The sitting position is standardized to the individual's body size and the task is performed in a comfortable self-paced speed and compensatory movements are not constrained. The intention is to keep the task natural and close to a real-life situation to improve the ecological validity of the protocol. A 5-camera motion capture system is used to gather 3D coordinate positions from 9 retroreflective markers positioned on anatomical landmarks of the arm, trunk, and face. A simple single marker placement is used to ensure the feasibility of the protocol in clinical settings. Custom-made Matlab software provides automated and fast analyses of movement data. Temporal kinematics of movement time, velocity, peak velocity, time of peak velocity, and smoothness (number of movement units) along with spatial angular kinematics of shoulder and elbow joint as well as trunk movements are calculated. The drinking task is a valid assessment for individuals with moderate and mild upper extremity impairment. The construct, discriminative and concurrent validity along with responsiveness (sensitivity to change) of the kinematic variables obtained from the drinking task have been established.

Video Link

The video component of this article can be found at https://www.jove.com/video/57228/

Introduction

Kinematic analysis describes the movements of the body through space and time, including linear and angular displacements, velocities, and accelerations. The optoelectronic motion capture systems use multiple high-speed cameras that either send out infra-red light signals to capture the reflections from passive markers placed on the body or transmit the movement data from active markers containing infrared emitting diodes. These systems are considered as 'gold standard' for the acquisition of kinematic data[1]. These systems are valued for their high accuracy and flexibility in measurements of diverse tasks. Kinematic measures have shown to be effective in capturing smaller changes in movement performance and quality that may be undetected with traditional clinical scales[2,3]. It has been suggested that kinematics should be used for distinction between true recovery (restoration of premorbid movement characteristics) and the use of compensatory (alternative) movement patterns during the accomplishment of a task[4,5].

Upper extremity movements can be quantified using end-point kinematics, generally obtained from a hand marker, and angular kinematics from joints and segments (*i.e.*, trunk). End-point kinematics provide information about trajectories, speed, temporal movement strategies, precision, straightness, and smoothness, while angular kinematics characterize movement patterns in terms of temporal and spatial joint and segment angles, angular velocities, and interjoint coordination. End-point kinematics, such as, movement time, speed, and smoothness are effective to capture the deficits and improvements in movement performance after stroke[6,7,8] and angular kinematics show whether the movements of joints and body segments are optimal for a specific task. Kinematics from people with impairments are often compared with movement performance in individuals without impairments[8,9]. End-point and angular kinematics are correlated in a way that a movement performed with effective speed, smoothness, and precision will require good movement control, coordination, and use of effective and optimal movement patterns. For example, a patient with stroke who moves slowly usually also shows decreased smoothness (increased number of movement units), lower maximum velocity, and increased trunk displacement[8]. On the other hand, improvements in endpoint kinematics, such as movement speed and smoothness might occur independently from the changes of compensatory movement strategies of trunk and arm[10]. It has been established that kinematic analysis may provide additional and more precise information about how the task is accomplished after an injury or disease, which in turn is essential for individualized effective treatment to reach optimal motor recovery[11]. Kinematic analysis is increasingly used in clinical studies to describe the movements in people with upper extremity impairments after stroke[8,9], to evaluate motor recovery[7,12,13] or to determine the effectiveness of therapeutic interventions[10,14].

Movement tasks often studied in stroke are pointing and reaching, although the use of functional tasks that incorporate manipulation of real everyday objects is increasing[1]. Since kinematics of reaching depend on the experimental constraints such as the selection of objects and the goal of the task[15], it is essential to assess movements during purposeful and functional tasks in which the real difficulties in individual's daily life will be reflected more closely.

Thus, the aim of this paper is to provide a detailed description of a simple standardized protocol used for kinematic analysis of a purposeful and functional task, drinking task, applied to individuals with upper extremity impairments in acute and chronic stages after stroke. Results from the validation of this protocol for individuals with moderate and mild stroke impairment will be summarized.

Protocol

All methods described here have been part of the studies approved by the Regional Ethical Review Board in Gothenburg, Sweden (318-04, 225-08).

1. Setting up the Motion Capture System

1. Mount 4 cameras on the wall approximately 1.5 - 3 m away from the measurement area at the height of 1.5 - 2.5 m facing the measurement area. Mount one camera on ceiling just above the measurement area (**Figure 1**). Start the camera system.
2. Place the L-shape calibration frame on the table with the short axis in line with the edge of the table and the long axis pointing forward.
NOTE: The coordinate system is defined with X-axes directed forward (anteriorly in the sagittal plane), Y-axis directed laterally (in the frontal plane), and Z-axis directed upward (superiorly, perpendicular to the transversal plane).
3. Open the 3D tracking and data acquisition software (Track Manager), start calibration by selecting **Capture | Calibrate**, enter the calibration time of 30 s and click **OK**.
4. Move the wand in all directions throughout the entire measurement area (75 × 75 × 65 cm) above the chair and table to ensure that all 5 cameras capture the wand in as many orientations as possible[16,17]. After the calibration, the results show on the screen. Accept calibration residuals below 0.5 mm.
5. Have the subject, wearing a sleeveless top, sit in a in a height adjustable chair with their back against the chair´s back, the upper arm in neutral adducted position, the palm of the hand resting at the table and the wrist aligned to the edge of the table. Check that the knee, hip, and elbow angles are approximately 90°.
6. Place the retroreflective passive markers with double-adhesive tape on the skeletal landmarks[18] on the tested hand (third metacarpophalangeal joint), wrist (styloid process of ulna), elbow (lateral epicondyle), right and left shoulder (middle part of acromion), thorax (upper part of sternum), and forehead (notch between eyebrows).
7. Place two markers on the cup (upper and lower edge).

2. Procedures for Motion Capture of the Drinking Task

1. Place the hard-plastic cup (diameter of 7 cm, height of 9.5 cm) with 100 mL of water 30 cm from the table edge, in the midline of the body. The position of cup on the table is selected deliberately to keep the task performance natural and close to real-life situation.
2. Ask the subject to perform the drinking task in a comfortable self-paced speed by i) reaching and grasping the cup, ii) lifting the cup from the table towards mouth, iii) taking a drink (one sip), iv) placing the cup back on the table behind a marked line (30 cm from the table edge), and v) returning to the initial position with the hand on the edge of the table.
3. Ensure that subject understands the instructions and can reach the cup comfortably with the less-affected arm without leaning forward.
4. Prior each recording, ensure that the start position (initial position) is correct, ask the subject to be ready, start the capture manually and give verbal instruction "you can start now."
5. When the subject finishes the task, stop the recording manually.
6. Record five trials with short pause between each trial (approximately 30 s), starting with the less-affected arm.
7. Check that the data acquisition has been successful (95 - 100% data for each identified marker).
NOTE: Marker data is automatically transferred in real-time to the data acquisition software (Track Manager). A pre-defined Automatic Marker Identification (AIM) model is used for automatic identification of the markers.
8. When incomplete data are detected, perform extra trials after identifying the problem and adjusting the sitting or marker positions to ensure full visibility of the markers in order to obtain at least 3 successful trials.
NOTE: Possible problems that may occur are that markers may fall off or they are occluded from the cameras viewing angle, which results in incomplete data. However, the camera and marker set-up, as used in this protocol, produces data loss due to gaps only in very rare occasions. In total, the motion capture session takes approximately 10 - 15 min to complete.

3. Data Analysis

1. Transfer the recorded data from Track Manager directly into Matlab by clicking **File | Export | Directly into Matlab**.
2. Use the Matlab command at the command prompt: (>> workspace) to see the set of Matlab variables.
NOTE: Key Matlab variables containing data to be used in the instructions and in creating the analysis are:
QTMmeasurements.Frames - the number of frames captured
QTMmeasurements.FrameRate - the number of frames captured per second (240)
QTMmeasurements.Trajectories.Labeled.Count - number of labels (10)
QTMmeasurements.Trajectories.Labeled.Labels - labels as defined in the Track Manager

QTMmeasurements.Trajectories.Labeled.Data - measurement data in a 3D array of 10 x 3 x number of frames, where for each frame and each label the 3 coordinates are recorded

3. In Matlab, filter the x, y, z values using the (butter) and (filtfilt) instructions with a 6Hz second-order Butterworth filter in in both forward and reverse directions, giving a zero-phase distortion and forth-order filtering.
   NOTE: Example
   [b, a] = butter(2, 6/240/2); % Cutoff frequency 6Hz and with respect to ½ sampling frequency
   xfiltered = filtfilt(b, a, QTMmeasurements.Trajectories.Labeled(1,1,:));
4. In Matlab, create a program to use the x, y, z values for each frame sample and each label to calculate the kinematic variables such as tangential velocity of the hand, and joint angles. The kinematic variables are shown in **Table 2**.
5. In Matlab, create a program to break the sequence of samples into 5 logical phases: reaching, forward transport, drinking, back transport, and returning the hand to the initial position (**Figure 2**). Definitions for start and end of each phase are showed in detail in **Table 1**.
6. In Matlab, use the (plot) instruction to create plots of positions, velocities, joints angles, and angle-angle diagrams.

Representative Results

The protocol described in this article has been applied to individuals with stroke and healthy controls[2,6,8,19,20,21]. In total, kinematic data from 111 individuals with stroke and 55 healthy controls have been analyzed in different studies. The upper extremity impairment after stroke was defined as moderate (FMA-UE score 32-57) or mild (FMA-UE score 58-66)[8,22,23,24]. In healthy controls, no significant differences were found between the dominant and non-dominant arm except for the peak velocity and therefore the non-dominant arm was chosen for comparison [2,8]. The majority of data was collected within a large longitudinal cohort study, the Stroke Arm Longitudinal study at University of Gothenburg (SALGOT), which includes a non-selected sample of 122 individuals with stroke and involves the assessments at 3 days post stroke and follow up at 10 days, 4 weeks, 3, 6, and 12 months[25].

In summary, our results show that the protocol is feasible in clinical settings since a large number of patients were tested as early as 3 days post-stroke at the acute hospitals stroke unit. Feasibility was also proven by the fact that two experienced physiotherapists managed to calibrate and use the motion capture system on daily basis without any larger technical problems (no support from the system providers was needed during the 3 years of data collection). The data quality was good and the pre-programmed automatic procedures for analyses could generally be applied. Only in few recordings, the phases were not detected correctly, often due to the extra movements in the beginning/end of the movement or when the movement speed was extremely low in patients with more severe impairments. In these cases, the extra trials were often used after a manual inspection of the plotted data. The test protocol demonstrated a good consistency in test-retest in healthy individuals and provided clear and accurate results[19].

The movements in every phase of the drinking task and for the entire task are slower (**Table 3**) in people with stroke, although the relative time spend in each phase is similar to controls[21]. Similarly, both tangential and angular velocities are lower in people with stroke compared to healthy controls (**Table 3**). The peak velocity occurred approximately at 38% of the total reaching time in stroke and a 46% in controls, which means that the deceleration phase was prolonged in stroke. This indicates that individuals with stroke need to rely more on the feedback driven movement control during the second half of reaching.

The velocity profiles in people with stroke are segmented and show multiple peaks, which is reflected in the high number of the movement units (NMU). The mean value for the NMU is significantly larger in individuals with stroke compared to controls. Individuals with stroke reach the cup with a more flexed elbow (less elbow extension) and with the shoulder more abducted while drinking compared to the healthy participants, which reflects the compensatory movement pattern in stroke. Even though the glass was positioned within the arm reach, individuals with stroke did lean forward (trunk displacement) approximately 8 cm compared to 3 cm in controls while performing the drinking task. Decreased interjoint coordination between shoulder and elbow joint in reaching was only observed in individuals with higher degree of impairment (moderate stroke) compared to controls. The exact values for kinematics and the magnitude of effect sizes for all groups are shown in **Table 3**.

The analysis of construct validity of kinematic variables from drinking task showed that movements after stroke can be described with two major factors, the end-point kinematics and kinematics describing angular movement patterns[8]. Altogether, five measures (movement time, peak velocity, number of movement units, peak angular velocity of elbow joint, and trunk displacement) explained 86% of the variance in kinematic data[8]. These results are in line with concurrent validity analyses, in which three kinematic variables, movement time (MT), movement smoothness (NMU) and trunk displacement (TD), together explained 67% of the total variance in scores of clinical assessments as assessed with Action Research Arm Test[20]. The discriminative validity between groups with mild and moderate arm impairment after stroke and controls was good for majority of kinematics, but the largest effect sizes were noted for the smoothness, total movement time, peak angular velocity of elbow (PAVE) and trunk displacement (**Table 3**)[8]. Shoulder abduction during drinking is also discriminative between moderate and mild stroke groups. In addition, the same four kinematic variables: MT, NMU, PAVE, and TD demonstrated to be effective in detecting real clinical improvement during the first 3 months after stroke[6]. Thus, it can be concluded that these four kinematic variables (MT, NMU, PAVE, TD) are reliable, valid and sensitive to changes (responsive) for assessment of upper extremity function and activity after stroke.

Figure 1: The 5-camera motion capture system set-up for drinking task. From each camera, infra-red light flashes reach retro-reflective markers and reproduce the 2D position of the marker in the cameras image sensor with high spatial resolution and accuracy in real-time. The 3D coordinates of the marker are created when two cameras are viewing the same marker from two different angles. Four cameras are mounted on the walls around the testing area facing slightly downward at approximately 2 m distance and one camera is mounted facing down from the ceiling above the measurement area. Please click here to view a larger version of this figure.

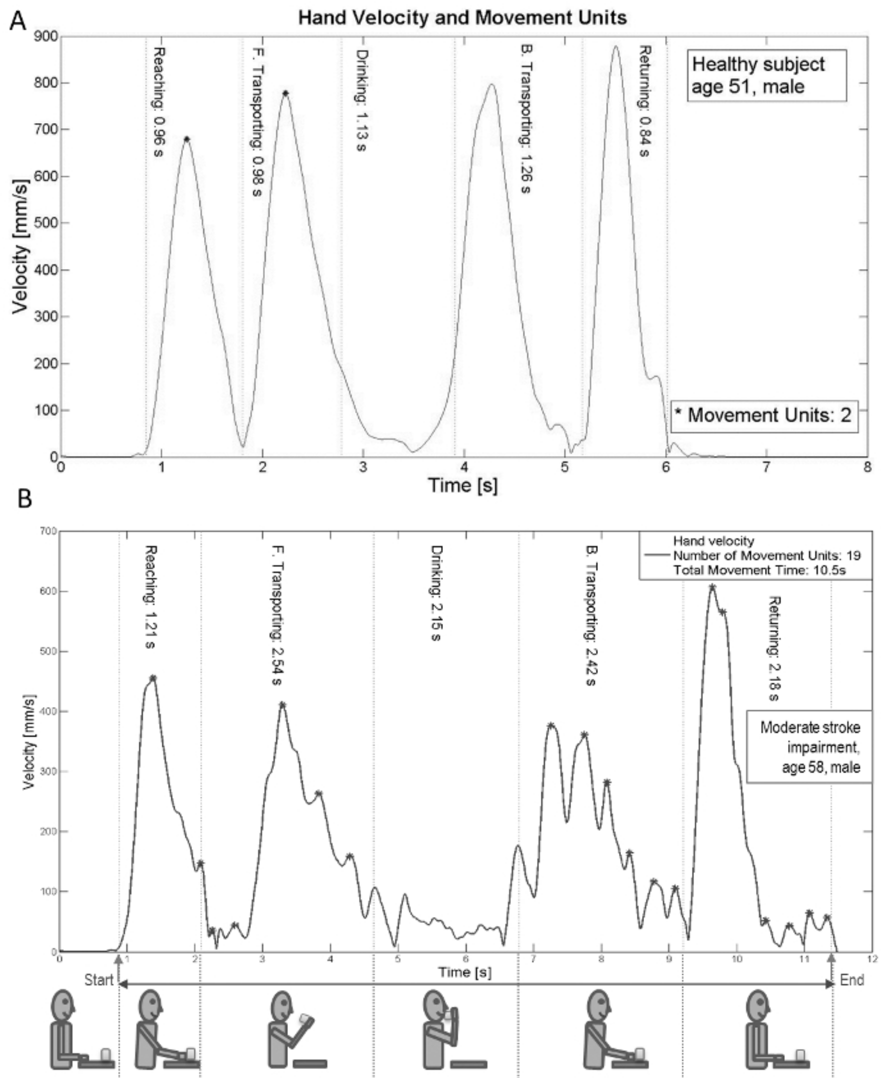

Figure 2: Representative velocity profiles for a healthy control (A) and an individual with moderate stroke impairment (B). The phases of the drinking task are shown. Please click here to view a larger version of this figure.

Phase name	Start	Detected by	End	Detected by
Reaching (includes grasping)	Hand movement begins	The hand marker velocity exceeds 2% of the peak velocity (searched backward from the peak velocity); if this value is higher than 20mm/s the start is tracked backward to a point where the velocity is not less or equal to 20 mm/s	Hand begins to move towards the mouth with the glass	Velocity of the glass exceeds 15 mm/s
Forward transport (glass to mouth)	Hand begins to move towards the mouth with the glass	Velocity of the glass exceeds 15 mm/s	Drinking begins	Distance between the face and glass marker is below 15% of steady state* during drinking
Drinking	Drinking begins	Distance between the face and glass marker is below 15% of steady state during drinking	Drinking ends	Distance between the face and glass marker exceeds 15% of steady state during drinking
Back transport (glass to table, includes release of grasp)	Hand begins to move to put the glass back to table	Distance between the face and glass marker exceeds 15% of steady state during drinking	Hand releases the glass and begins to move back to initial position	Velocity of the glass below 10 mm/s
Returning (hand back to initial position)	Hand releases the glass and begins to move back to initial position	Velocity of the glass below 10 mm/s	Hand is resting in initial position	Hand marker velocity returned to 2% of the peak velocity
*Steady state in the drinking phase indicates an averaged value of the 100 frames around the shortest distance between the face and glass marker				

Table 1: Phase definitions for the start and end of each phase of the drinking task.

Variable	Specification
End-point kinematics	Calculated from the hand marker
Movement time, s	Calculated for each phase and as total movement time for the entire task; definitions for start and stop are provided in Table 1
Peak tangential velocity, mm/s	Calculated for reaching phase, combines both arm and trunk movement
Time to peak hand velocity, s, %	Absolute and relative values for reaching, characteraizes movement strategy (acceleration and deceleration time)
Time to first velocity peak, s, %	Absolute and relative values for reaching, characteraizes the initial movement effort
Number of movement units, n	Calculated for reaching, forward transport, back transport, and returning phase. One movement unit is defined as a difference between a local minimum and next maximum velocity value that exceeds the amplitude limit of 20 mm/s, and the time between two subsequent peaks has to be at least 150 ms. The minimum value for drinking task is 4, at least one unit per movement phase. Those peaks reflect repetitive acceleration and deceleration during reaching and correspond to movement smoothness and efficiency.
Angular kinematics, degrees	Calculated for shoulder and elbow joint
Elbow extension	Minimum angle of elbow flexion detected in the reaching phase, determined by the angle between the vectors joining the elbow and wrist markers and the elbow and shoulder markers
Shoulder abduction	Maximum angle in frontal plane detected during reaching and drinking phase, respectively; determined by the angle between the vectors joining the shoulder and elbow markers and the vertical vector from the shoulder marker toward the hip
Shoulder flexion	Maximum angle in sagittal plane detected during reaching and drinking, respectively; determined by the angle between the vectors joining the shoulder and elbow markers and the vertical vector from the shoulder marker toward the hip
Peak angular velocity of the elbow joint, degrees/s	Peak velocity of the elbow extension detected during the reaching phase
Interjoint coordination, r	Temporal cross-correlation of zero time lag between the shoulder flexion and elbow extension during the reaching phase. A Pearson's correlation coefficient closer to 1 indicates stronger correlation and indicates that joint motion of the two joints is tightly coupled.
Trunk displacement, mm	Maximum displacement of the thorax marker from the initial position during the entire drinking task

Table 2: Definitions of kinematic variables used in studies presented in the representative results.

Kinematic variables, mean (SD)	**Healthy**	**Stroke**	**Effect size (healthy vs stroke)**	**Mild stroke**	**Effect size (healthy vs mild stroke)**	**Moderate stroke**	**Effect size (mild stroke vs moderate stroke)**
End-point kinematics							
Total movement time, s	6.49 (0.83)	11.4 (3.1)	0.54*	9.30 (1.68)	0.46*	13.3 (2.9)	0.44*
Number Movement Units, (smoothness), n	2.3 (0.3)	8.4 (4.2)	0.54*	5.4 (2.1)	0.42*	11.1 (3.6)	0.50*
Peak velocity in reach, mm/s	616 (93.8)	431 (82.7)	0.54*	471 (87.7)	0.37*	395 (62.0)	0.22*
Peak angular velocity elbow in reach, °/s	121.8 (25.3)	64.9 (20.5)	0.62*	78.0 (19.3)	0.57*	53.3 (13.6)	0.38*
Time to peak velocity in reach, %	46.0 (6.9)	38.4 (8.6)	0.20*	39.5 (8.7)	0.15*	37.5 (8.8)	0.01
Time to first peak in reach, %	42.5 (6.9)	27.1 (12.2)	0.39*	33.0 (9.9)	0.25*	21.8 (11.9)	0.22*
Angular joint kinematics							
Elbow extension in reach-to-grasp, degree	53.5 (7.8)	64.1 (11.5)	0.24*	60.5 (10.4)	0.13	67.2 (11.9)	0.09
Shoulder abduction in drinking, degree	30.1 (10.1)	47.6 (14.9)	0.33*	37.2 (5.3)	0.07	57.1 (14.5)	0.47*
Trunk Displacement, mm	26.7 (16.8)	77.2 (48.6)	0.34*	50.1 (22.9)	0.26*	101.7 (53.4)	0.30*
Interjoint coordination, Pearson r	0.96 (0.02)	0.82 (0.35)	0.08	0.95 (0.02)	0.03	0.69 (0.46)	0.14
* $p<0.05$; Effect size statistics are calculated as eta squared, η^2							

Table 3: Kinematic variables for individuals with stroke, for subgroups of moderate and mild upper extremity impairment along with healthy controls. Effect sizes for discrimination between groups above 0.4 (very large effect) are marked bold.

Discussion

The protocol can successfully be used to quantify the movement performance and quality in individuals with moderate and mild upper extremity sensorimotor impairments at all stages after stroke. The feasibility of this protocol has been proved in a clinical setting as early as 3 days post stroke, and showed that the system can be used by trained health professional without specific technical qualifications. Technical expertise is, however, needed to create and develop a program for data analysis. From this aspect, the upper extremity motion capture differs from gait analysis, in which ready-made analysis programs are generally directly provided by the manufacturers. In everyday life, arms and hands can be used in many different tasks involving manipulation and interaction with different object in various sizes, locations, and affordances. This makes each set-up unique. Further, different goals and constraints of the task will also affect the kinematic outcome, since the kinematics are highly task-specific. In the future, more efforts should be made to create a standardized protocol for kinematic analysis of basic tasks, such as, drinking, eating, taking hand to the mouth, and bimanual object manipulation, which would allow a better comparison of the results between different studies.

Based on our early experiences, with a 3-camera capture system, in which the problem with segmentations and gaps was observed, it can be suggested that a 5-camera system that allows different positions for cameras (and one above the measurement area) is optimal for the upper extremity analysis. For a clinically feasible measurement set-up, a simple set-up with limited number of markers and simplified analysis, as described in this protocol can be advocated. When the assessment of movement performance and quality aims to follow patients' recovery, make prediction of future outcomes, select optimal treatment options, or evaluate the effectiveness of treatment and rehabilitation interventions, a simple, easy to use method would be enough. On the other hand, a more comprehensive biomechanical analysis using cluster-based markers would be required for more detailed modeling, particularly when the axial joint rotations and shoulder complex are of interest.

Increased clinical use of kinematic analysis is advocated by many researches in the area of neurology and stroke rehabilitation. Objective and valid methods for evaluation of motor function during natural activities and tasks are of high interest among clinicians and researchers. A recent consensus paper recommends adding kinematic measures in future stroke trials alongside with clinical assessments to distinguish between true recovery and compensation[11]. Challenges remain though, to determine a core set of kinematic outcomes and tasks for inclusion in trials, and to encourage broader collaboration between investigators to reach consensus[11]. The current 3D motion capture protocol together with published validation studies of this protocol can be one step on that direction.

Disclosures

The authors have nothing to disclose.

Acknowledgements

Special thanks to Bo Johnels, Nasser Hosseini, Roy Tranberg and Patrik Almström for help with the initiation of this project. The research data presented in this protocol was gathered at the Sahlgrenska University Hospital.

References

1. Alt Murphy, M., & Häger, C. K. Kinematic analysis of the upper extremity after stroke - how far have we reached and what have we grasped? *Physical Therapy Reviews.* **20** (3), 137-155 (2015).
2. Bustren, E. L., Sunnerhagen, K. S., & Alt Murphy, M. Movement Kinematics of the Ipsilesional Upper Extremity in Persons With Moderate or Mild Stroke. *Neurorehab Neural Re.* **31** (4), 376-386 (2017).
3. Sivan, M., O'Connor, R. J., Makower, S., Levesley, M., & Bhakta, B. Systematic review of outcome measures used in the evaluation of robot-assisted upper limb exercise in stroke. *J Rehabil Med.* **43** (3), 181-189 (2011).
4. Demers, M., & Levin, M. F. Do Activity Level Outcome Measures Commonly Used in Neurological Practice Assess Upper-Limb Movement Quality? *Neurorehab Neural Re.* **31** (7), 623-637 (2017).
5. Levin, M. F., Kleim, J. A., & Wolf, S. L. What do motor "recovery" and "compensation" mean in patients following stroke? *Neurorehab Neural Re.* **23** (4), 313-319 (2009).
6. Alt Murphy, M., Willen, C., & Sunnerhagen, K. S. Responsiveness of Upper Extremity Kinematic Measures and Clinical Improvement During the First Three Months After Stroke. *Neurorehab Neural Re.* **27** (9), 844-853 (2013).
7. van Dokkum, L. *et al.* The contribution of kinematics in the assessment of upper limb motor recovery early after stroke. *Neurorehab Neural Re.* **28** (1), 4-12 (2014).
8. Alt Murphy, M., Willen, C., & Sunnerhagen, K. S. Kinematic variables quantifying upper-extremity performance after stroke during reaching and drinking from a glass. *Neurorehab Neural Re.* **25** (1), 71-80 (2011).
9. Subramanian, S. K., Yamanaka, J., Chilingaryan, G., & Levin, M. F. Validity of movement pattern kinematics as measures of arm motor impairment poststroke. *Stroke.* **41** (10), 2303-2308 (2010).
10. Michaelsen, S. M., Dannenbaum, R., & Levin, M. F. Task-specific training with trunk restraint on arm recovery in stroke: randomized control trial. *Stroke.* **37** (1), 186-192 (2006).
11. Kwakkel, G. *et al.* Standardized measurement of sensorimotor recovery in stroke trials: Consensus-based core recommendations from the Stroke Recovery and Rehabilitation Roundtable. *Int J Stroke.* **12** (5), 451-461 (2017).
12. Wagner, J. M., Lang, C. E., Sahrmann, S. A., Edwards, D. F., & Dromerick, A. W. Sensorimotor impairments and reaching performance in subjects with poststroke hemiparesis during the first few months of recovery. *Phys Ther.* **87** (6), 751-765 (2007).
13. van Kordelaar, J., van Wegen, E., & Kwakkel, G. Impact of time on quality of motor control of the paretic upper limb after stroke. *Arch Phys Med Rehab.* **95** (2), 338-344 (2014).
14. Thielman, G., Kaminski, T., & Gentile, A. M. Rehabilitation of reaching after stroke: comparing 2 training protocols utilizing trunk restraint. *Neurorehab Neural Re.* **22** (6), 697-705 (2008).
15. Armbruster, C., & Spijkers, W. Movement planning in prehension: do intended actions influence the initial reach and grasp movement? *Motor Control.* **10** (4), 311-329 (2006).
16. Qualisys. *Qualisys Track Manager user manual.* Qualisys Medical AB, Gothenburg. (2008).
17. Alt Murphy, M., Banina, M. C., & Levin, M. F. Perceptuo-motor planning during functional reaching after stroke. *Exp Brain Res.* (2017).
18. Sint Jan, S. V. *Color atlas of skeletal landmark definitions : guidelines for reproducible manual and virtual palpations.* Churchill Livingstone. (2007).
19. Alt Murphy, M., Sunnerhagen, K. S., Johnels, B., & Willen, C. Three-dimensional kinematic motion analysis of a daily activity drinking from a glass: a pilot study. *J Neuroeng Rehabil.* **3** 18 (2006).
20. Alt Murphy, M., Willen, C., & Sunnerhagen, K. S. Movement kinematics during a drinking task are associated with the activity capacity level after stroke. *Neurorehab Neural Re.* **26** (9), 1106-1115 (2012).
21. Alt Murphy, M. *Development and validation of upper extremity kinematic movement analysis for people with stroke. Reaching and drinking from a glass.* Doctor of Philosophy (Medicine) thesis, University of Gothenburg, (2013).
22. Persson, H. C., Alt Murphy, M., Danielsson, A., Lundgren-Nilsson, A., & Sunnerhagen, K. S. A cohort study investigating a simple, early assessment to predict upper extremity function after stroke - a part of the SALGOT study. *BMC Neurol.* **15** 92 (2015).
23. Hoonhorst, M. H. *et al.* How Do Fugl-Meyer Arm Motor Scores Relate to Dexterity According to the Action Research Arm Test at 6 Months Poststroke? *Arch Phys Med Rehab.* **96** (10), 1845-1849 (2015).
24. Pang, M. Y., Harris, J. E., & Eng, J. J. A community-based upper-extremity group exercise program improves motor function and performance of functional activities in chronic stroke: a randomized controlled trial. *Arch Phys Med Rehab.* **87** (1), 1-9 (2006).
25. Alt Murphy, M. *et al.* SALGOT - Stroke Arm Longitudinal study at the University of Gothenburg, prospective cohort study protocol. *BMC Neurol.* **11** 56 (2011).