

Methodological considerations for kinematic analysis of upper limbs in healthy and poststroke adults. Part I: A systematic review of sampling and motor tasks

Inês Albuquerque Mesquita, Ana Rita Vieira Pinheiro, Miguel Fernando Paiva Velhote Correia & Cláudia Isabel Costa da Silva

To cite this article: Inês Albuquerque Mesquita, Ana Rita Vieira Pinheiro, Miguel Fernando Paiva Velhote Correia & Cláudia Isabel Costa da Silva (2018): Methodological considerations for kinematic analysis of upper limbs in healthy and poststroke adults. Part I: A systematic review of sampling and motor tasks, Topics in Stroke Rehabilitation

To link to this article: <https://doi.org/10.1080/10749357.2018.1551953>



Published online: 29 Nov 2018.







Submit your article to this journal [↗](#)



View Crossmark data [↗](#)



Methodological considerations for kinematic analysis of upper limbs in healthy and poststroke adults. Part I: A systematic review of sampling and motor tasks

Inês Albuquerque Mesquita ^a, Ana Rita Vieira Pinheiro ^{b,c}, Miguel Fernando Paiva Velhote Correia ^{d,e}
and Cláudia Isabel Costa da Silva ^f

^aDepartment of Functional Sciences and Center for Research in Rehabilitation (CIR), School of Health Sciences of Polytechnic Institute of Porto (ESS-P.Porto), Porto, Portugal; ^bSchool of Health Sciences, University of Aveiro, Aveiro, Portugal; ^cCenter for Research in Rehabilitation (CIR), School of Health Sciences of Polytechnic Institute of Porto (ESS-P.Porto), Porto, Portugal; ^dDepartment of Electrical and Computer Engineering, Faculty of Engineering, University of Porto (FEUP), Porto, Portugal; ^eInstitute for Systems and Computer Engineering, Technology and Science (INESC TEC), Porto, Portugal; ^fDepartment of Physiotherapy, and Center for Research in Rehabilitation (CIR), School of Health Sciences of Polytechnic Institute of Porto (ESS-P.Porto), Porto, Portugal

ABSTRACT

Background and Purpose: The purpose of this study was to review the methods used to analyze the kinematics of upper limbs (ULs) of healthy and poststroke adults, namely specificities of sampling and motor tasks.

Summary of review: A database of articles published in the last decade was compiled using the following search terms combinations: (“upper extremity” OR “upper limb” OR arm) AND (kinematics OR motion OR movement) AND (analysis OR assessment OR measurement). The articles included in this review (1) had the purpose to analyze objectively a three-dimension kinematics of ULs, (2) studied functional movements or activities of daily living (ADL) involving uppers limbs, and (3) studied healthy and/or poststroke adults. Fourteen articles were included (four studied a healthy sample, three analyzed poststroke patients, and seven examined both poststroke and healthy participants).

Conclusion: Most of the recommended demographic and stroke information, such as some pre-existing conditions to stroke, initial stroke severity, and stroke location, were not collected by all or most of the articles. Time poststroke onset was presented in all articles but showed great variability. Few articles identified anthropometric characteristics and adjusted task environment to them. Most of the samples were composed mainly by males and had a low mean age, which does not represent poststroke population. Most articles analyzed “functional movements”, namely simulations of ADL.

Implication of key findings: Future research should identify the recommended information to allow an adequate stratification. Acute phase after stroke, real ADL with different complexities, and ipsilesional UL should be studied.

ARTICLE HISTORY

Received 5 April 2018
Accepted 18 November 2018

KEYWORDS

Upper extremity; kinematic assessment; stroke; healthy adults; demographic information; stroke information; activities of daily living

1. Introduction

Recovery and a return to a full life following stroke are the main goals for stroke survivors, their families and caregivers, and health professionals.¹ However, more than 80% of stroke patients experience acute sensorimotor dysfunction of the contralesional upper limb (UL), which becomes chronic for more than 40% of the patients.² According to the Stroke Recovery and Rehabilitation Roundtable (SRRR), the ability to understand the recovery mechanisms and to devise better treatments is hampered by the lack of a standardized approach to measurement in stroke recovery research.³ Insufficient attention has also been paid to patient's recruitment and stratification.⁴ The magnitude of change and likelihood of achieving clinically meaningful improvement in response to specific therapies will depend on age, stroke severity, physical, and other factors including pre-existing comorbid conditions.³ The respective contributions of these factors have yet to be fully understood.³

Recently, the SRRR presented the results of a consensus meeting about measurement standards and information they suggest should be collected in all future stroke recovery trials.³ Recommendations for demographic and stroke information include age, sex, medical history, stroke severity, type and location, among others.³ Moreover, recovery trials should start early poststroke and include both core clinical measures (e.g. the National Institute of Health Stroke Scale [NIHSS] and the Fugl-Meyer Assessment [FMA]) and kinematics assessed serially at standard intervals poststroke.³ While clinical measures can detect change, they cannot differentiate restitution from compensation. Kinematics' parameters are presented as one of the best ways for this purpose and to improve the understanding about the mechanisms that drive motor recovery.³ However, a core set of kinematic outcomes needs to be established.³

In fact, in the last decade, three-dimensional (3D) kinematics of ULs of healthy adults and neurological patients, mostly after stroke, were studied in order to quantify movement objectively

and accurately.⁵ The 3D systems have been shown to be highly accurate and able to capture simultaneous multi-segmental movement characteristics of human motion, providing detailed knowledge not available through conventional two-dimensional and observational analyses.⁶ Can the mentioned studies be used as reliable references? Have they complied with the recent recommendations regarding the collection of demographic and stroke information? In parallel, were the analyzed healthy individuals' characteristics matching the poststroke individuals to provide a database that could be used as a reference? Similarly to poststroke adults, it is necessary to analyze the information that was collected about healthy/control participants, and its characteristics, to check if they can be used as a reference for stroke rehabilitation and research. Therefore, in this review, we explore the collected information about the samples including healthy participants (isolated and/or as a control) and poststroke adults.

There are also four major factors on which kinematic analysis of ULs depends, which should not be overlooked: (a) motion capture systems, (b) movement category, i.e. motor tasks, (c) kinematic metrics extracted, (d) and interpretation of these kinematic metrics.⁷ Considering the manifested urgency in presenting additional recommendations for the use of kinematic measures in stroke recovery and rehabilitation research,³ we have also reviewed these factors. To make reading easier, we split this review into two parts. So, in this first part, besides sampling characteristics, we review the motor tasks used to analyze the ULs kinematics.

The motor tasks generally used to study the function of ULs can be categorized into functional movements (reaching movements and path drawing) and activities of daily living (ADL).^{5,7,8} Several authors^{5,9–11} defend that the analysis of goal-oriented tasks, such as performing an ADL, increases the validity of studies. However, this may complicate the kinematic analysis of ULs since, unlike lower limbs, they are involved in several important ADL.¹² Furthermore, most stroke survivors are far from performing any ADL due to impairments in prehensile function.¹³ Therefore, what kind of movement category is being studied and what is its complexity level?

Based on these questions, the aim of this study was to review and discuss the methods used to analyze the kinematics of ULs of healthy and poststroke adults, namely the specificities of sampling and performed motor tasks.

2. Methods

The study was conducted using the “PRISMA guidelines for a Systematic Review” (“Preferred Reporting Items for Systematic Reviews and Meta-Analysis”).¹⁴

2.1 Research questions

The two major research questions of this review were:

- (1) What was the collected information, and its characteristics, about stroke and healthy/control samples found in literature that analyzed the ULs kinematics?
- (2) What were the motor tasks performed in these same studies and in which movement category are they included?

2.2 Search strategy

Two reviewers performed an electronic search on PubMed database and the resource aggregator B-on, namely using the EBSCO EDS interface, to find all the articles published between 1 January 2007 and 31 December 2017 on the topic of UL kinematic analysis in healthy and poststroke adults. The following search terms combinations were used: (“upper extremity” OR “upper limb” OR arm) AND (kinematics OR motion OR movement) AND (analysis OR assessment OR measurement). The search terms were limited to titles of available full scientific papers, published in academic journals, and written in English. The reference lists of all articles were also scanned to identify other potential eligible articles.

2.3 Inclusion and exclusion criteria

The articles included in this review (1) had the purpose to analyze objectively 3D kinematics of ULs; (2) studied functional movements of ULs, or ADL involving ULs (according to van Tuijl et al.⁸), clearly described; and (3) studied healthy living adult (>19 years old) humans and/or adult humans with stroke sequelae. The articles excluded from this review (1) analyzed a single UL joint rather the UL itself, since the recommendations³ suggest UL assessment rather than isolated joints; (2) studied athletes, to eliminate the sport gesture influence on the UL movement; (3) used robots, exoskeletons, or virtual realities, to study more realistic contexts; (4) were meta-analyses, reviews, case reports, pilot studies, technical notes, or studies published as conference proceedings.

2.4 Assessment of methodologic quality

The articles included in this systematic review were evaluated using a quality index proposed by Downs and Black.¹⁵ West et al.¹⁶ identified the Downs and Black checklist as being consistent with 18 other recommended quality assessment systems. Studies meeting <60% criteria were considered low quality, ≥60% to <75% moderate quality, and ≥75% high quality. The two searching reviewers independently performed the quality assessment for each of the included articles. Consensus regarding the quality index score for each article was achieved by both authors.

2.5 Data extraction

Data from the included articles were extracted by one reviewer and then checked by a second reviewer using a data extraction table (Table 1) which identified author identification, year of publication, sample used, motor tasks, and quality index score.

3. Results

3.1 Search yield

The search strategy revealed 471 results and 3 other articles were identified through the reference lists (Table 2). After an initial examination, 329 were rejected as copies of the same paper; the remaining 145 articles were then reviewed by the 2

Table 1. Sample characteristics, motor tasks, and quality index score.

Reference	Sample characteristics	Motor task(s)	Quality index score (%)
van Andel et al. [12]	<p>Healthy participants</p> <ul style="list-style-type: none"> • $n = 10$, (4 F, 6 M) • Age: 28.5 ± 5.7 years old • Handedness: right-handed (9) and left-handed (1) 	<p>(1) Hand to the contralateral shoulder;</p> <p>(2) Hand to mouth/drinking;</p> <p>(3) Combing hair (hand to the fore head and toward the neck);</p> <p>(4) Hand to back pocket.</p> <p>All tasks were performed with right UL. Subjects were asked to copy the movements of the instructor standing in front of them.</p>	34
Wagner et al. [20]	<p>Poststroke participants</p> <ul style="list-style-type: none"> • $n = 14$ (3 F, 11 M) • Age: 59.9 ± 14.6 (22–82) years old • Time poststroke onset: 14.0 ± 6.5 months • FMA total: 89.4 ± 10.2 • FMA-UE motor: 34.7 ± 9.0 • FMA-UE shoulder/elbow: 16.8 ± 6.5 • MAS: 0.67 ± 0.53 	<p>(1) Reach forward toward a 2.2-cm-wide piece of tape located at the superior end of a 0.5-cm-diameter vertical rod attached to a solid circular base;</p> <p>(2) Four different reaching tasks produced by the combination of 2 target heights (low and high [109 and 153 cm from the floor, respectively]) and 2 instructed speeds of movement (self-selected and fast as possible).</p> <p>The target was positioned directly in front of the “affected” (contralateral to the lesion) shoulder at 110% of arm’s length. Participants performed the tasks seated in a straight-back chair. The trunk was stabilized to the back of the chair to minimize compensatory trunk movements.</p>	63
Thies et al. [22]	<p>Poststroke participants</p> <ul style="list-style-type: none"> • $n = 6$ (2 F, 4 M) • Age: (33–83) years old • Time poststroke onset: (6–48) months • Handedness: right-handed (6) • Affected side: right (3), left (3) • Motricity index: 63–76/100 • Ashworth scale: 0–3 • Light touch discrimination (wrist, hand): 0–6/6 • Movement detection (shoulder, elbow, wrist, and thumb): 3–6/6 <p>Healthy control participants</p> <ul style="list-style-type: none"> • $n = 6$ <p>Age, sex, and right/left hand dominance of each control participant corresponded to his/her respective poststroke participant.</p>	<p>(1) Unilateral task: Drinking from a glass. Poststroke participants performed the task with their affected UL, and controls had to use the same UL as their corresponding match;</p> <p>(2) Bilateral task: moving a plate. Manipulation of the plate contained a small upward lift of the plate in front of the torso, followed by a sideways translation of the plate toward the side where the plate was then lowered onto the table.</p> <p>The location of each object, at a self-reported comfortable distance to the subject, was likewise marked on the table’s cover. Care was taken that the object was placed within a distance that did not require engagement of the torso during task performance. Both tasks were performed at a self-selected comfortable speed.</p>	69
Aizawa et al. [18]	<p>Healthy participants</p> <ul style="list-style-type: none"> • $n = 20$ (10 F, 10 M) • Age: 23 ± 5 (18–34) years old • Height: 166 ± 10 (149–182) cm • Weight: 61 ± 11 (47–78) kg • Body mass index: 22 ± 2.3 (17–27) kg/m² • Handedness: right-handed (20) 	<p>Bilateral 16 movement tasks related to personal care/hygiene and diet/food preparation: (1) touching the ipsilateral axilla; (2) touching the opposite axilla; (3) touching the mouth; (4) touching the ipsilateral ear; (5) touching the opposite ear; (6) touching the forehead; (7) touching the perineum; (8) touching the back; (9) fastening a button at neck level; (10) fastening a button at navel level; (11) washing the face; (12) putting on a necklace; (13) combing air; (14) eating with a spoon; (15) pouring water into a glass; (16) drinking with a glass.</p> <p>An instructor explained the basic pattern of the movement tasks. All tasks were performed at a comfortable speed.</p>	56

(Continued)

Table 1. (Continued).

Reference	Sample characteristics	Motor task(s)	Quality index score (%)
Chen et al. [17]	<p>Healthy participants</p> <ul style="list-style-type: none"> • $n = 10$ (0 F, 10 M) • Age: 25 ± 3 years old • Height: 170 ± 10 cm • Weight: 65.2 ± 4 kg • Handedness: right-handed (10) 	Tasks (1), (2), and (3) of van Andel et al. (2008). [12] Subjects were asked to follow the movements of the instructor standing in front of them.	50
Murphy et al. [9]	<p>Poststroke participants</p> <ul style="list-style-type: none"> • $n = 19$ • Age: 61 ± 11.1 (41–79) years old • Time poststroke onset: 18.9 ± 16.4 months • Stroke type: infarct (14) and hemorrhage (5) • Stroke side: right (12), left (7) • Handedness: right-handed (19) • FMA-UE: 53.4 ± 8.7 (39–64) <ul style="list-style-type: none"> ○ Moderate arm impairment: 10 ○ Mild arm impairment: 9 • Sensation: 3–12/12 • Passive range of movement: 17–24/24 • Pain: 12–24/24 <p>Healthy control participants</p> <ul style="list-style-type: none"> • $n = 19$ (9 F, 10 M) • Age: 57.3 (41–78) years old • Handedness: right-handed (19) 	<p>(1) Drinking</p> <p>Participants were seated on a 46-cm high, straight-back chair in front of a 74-cm high table. The drinking glass was 7 cm in diameter and 9.5 cm high and was filled with 100 mL water. It was placed 30 cm from the table edge in the midline of the body. Participants were instructed to sit against the chair back during the whole task, but the sitting position was not restrained, and compensatory movements were allowed if needed. Participants performed the drinking task starting randomly with their right or left arm. They were instructed to initiate the drinking task at a comfortable self-paced speed.</p>	72
Patterson et al. [23]	<p>Poststroke participants</p> <ul style="list-style-type: none"> • $n = 18$ (5 F, 13 M) • Age: 67.6 ± 8.1 (47–78) years old • Time poststroke onset: (7–174) months • Stroke type: ischemic (18) • Affected side: right (7), left (11) • Stroke location: middle cerebral artery (6), striatocapsular (2), lacunar (2), middle/posterior cerebral artery (1), medullary/brainstem (1), medial medullary (1), posterior cerebellar (1), basal ganglia (1), posterior periventricular white matter (1), pontine (1), brainstem lacunar (1) • FMA-UE: 27–58 <ul style="list-style-type: none"> ○ Severe arm impairment: 9 ○ Moderate arm impairment: 8 ○ Mild arm impairment: 1 	<p>(1) Reach and touch a piece of tape affixed to the table at midline at two different speeds: at a self-selected comfortable pace and as quickly as possible.</p> <p>(2) Reach and grasp cylindrical cans of different sizes (208 mm circumference and 270 mm circumference) but of the same weight placed on the table directly in front of the reaching hand</p>	59

(Continued)

Table 1. (Continued).

Reference	Sample characteristics	Motor task(s)	Quality index score (%)
Finley et al. [24]	<p>Poststroke participants</p> <ul style="list-style-type: none"> ● $n = 15$ (6 F, 9 M) ● Age: 62.4 ± 8.4 (48–76) years old ● Time poststroke onset: 74.1 ± 50.1 (12–171.0) months ● Side of hemiparesis: right (7), left (8) ● FMA-UE: 48.5 ± 18.4 (15–64) <ul style="list-style-type: none"> ○ Severe arm impairment: 3 ○ Moderate arm impairment: 2 ○ Mild arm impairment: 10 ● Handedness: right-handed (15) <p>Healthy control participants</p> <ul style="list-style-type: none"> ● $n = 15$ (7 F, 8 M) ● Age: 60.3 ± 10.6 years old ● Handedness: right-handed (15) 	<p>(1) Reach and touch a target located to left and right of midline, 45° in the horizontal plane and return.</p> <p>Participants were seated with a cross-chest harness trunk restraint system preventing forward flexion. They were seated at such a height that the extremity resting on the table created a 60–70° humerothoracic angle, with a center of the template at the participant's maximal reaching distance, placed directly in front of the individuals at midline. Movements were performed unilaterally with each UL at a self-selected, comfortable speed and at a fast speed to targets placed ipsilateral to the moving limb and contralateral to the limb. The order of reaching limb, target location, and speed movement was randomized.</p>	75
Murphy et al. [10]	<p>Poststroke participants</p> <ul style="list-style-type: none"> ● $n = 30$ (15 F, 15 M) ● Age: 66.4 ± 12.8 years old ● Time poststroke onset: 2.5 ± 2.4 months ● Stroke type: ischemic (18), hemorrhagic (12) ● Affected side: right (14), left (16) ● FMA-UE: 53.6 ± 9.1 (32–64) ● ARAT: 47.6 ± 8.8 ● ABILHAND: 2.2 ± 1.7 	<p>(1) Drinking</p> <p>The drinking glass was filled with 100 mL water and placed 30 cm from the table edge in the midline of the body, corresponding approximately to a distance of 80% of arm's length. Participants were sitting in a height-adjustable chair with their back against the chair's back, but the position was not restrained and compensatory movements were allowed if needed. The task was performed at a comfortable self-paced speed, and both arms were tested starting with the nonaffected arm.</p>	72
Murphy et al. [21]	<p>Poststroke participants (subgroup 1)</p> <ul style="list-style-type: none"> ● $n = 27$ (12 F, 15 M) ● Age: 64.0 ± 12.9 years old ● Time poststroke onset: 9.3 ± 9.4 days ● Stroke type: ischemic (26), hemorrhagic (1) ● Hemiparesis side: right (13) left (14) ● FMA-UE: 60.7 ± 4.7 ● ARAT: 55.2 ± 1.9 <p>Poststroke participants (subgroup 2)</p> <ul style="list-style-type: none"> ● $n = 24$ (8 F, 16 M) ● Age: 65.6 ± 10.6 years old ● Time poststroke onset: 9.8 ± 10.9 days ● Stroke type: ischemic (18), hemorrhagic (6) ● Hemiparesis side: right (8) left (16) ● FMA-UE: 50.6 ± 9.4 ● ARAT: 42.0 ± 7.1 	<p>The same task of Murphy et al.¹⁰ but only the affected UL were used.</p>	78

(Continued)

Table 1. (Continued).

Reference	Sample characteristics	Motor task(s)	Quality index score (%)
van Dokkum et al. [25]	<p>Poststroke participants</p> <ul style="list-style-type: none"> • $n = 13$ (3 F, 10 M) • Age: 63.9 ± 9.4 (43–81) years old • Time poststroke onset: 21 ± 7 (13–30) days • Stroke type: ischemic (9), hemorrhagic (4) • Damaged hemisphere: right (5), left (8) • Localization: deep/subcortical (5), deep + superficial (5), superficial/cortical (3) • Hemiplegia side: left (6) • FMA-UE: (4–62) 	<p>(1) "Reach-to-grasp" a 5-cm ball lying on a table placed 20 cm in front and bring the ball to a target location 5 cm from the edge of the table.</p> <p>The task was executed first with the nonparetic limb, then with the paretic limb. Pace was self-selected. Participants were seated in front of a table at waist height so that shoulders remained at rest, elbows were flexed 90°, and hands (palms down) could be placed easily at their respective starting positions. Participants' trunks were strapped to prevent potential compensating movements.</p>	59
Kim et al. [11]	<p>Poststroke participants</p> <ul style="list-style-type: none"> • $n = 16$ (3 F, 13 M) • Age: 49.8 ± 7.3 (15–70) years old • Time poststroke onset: (6–108) months • Impaired UL function: right (8), left (8) • Height: 167.9 ± 3.8 cm • Weight: 67.9 ± 4.2 kg <p>Healthy control participants</p> <ul style="list-style-type: none"> • $n = 32$ (15F, 17M) • Age: 25.3 ± 2.4 years old • Height: 168.7 ± 3.9 cm • Weight: 62.0 ± 5.4 kg • Handedness: right-handed (30) and left-handed (2) 	<p>(1) Drinking.</p> <p>Each subject was instructed how to perform the drinking task. All participants were seated at a right angle in a chair with their UL supported on a table. The UL was placed against the trunk and the elbow was flexed at 90°. In every case, the subject-to-table distance was regularly maintained, and the sitting and table heights could be adapted to obtain the same starting position for all participants.</p>	50
Ozturk et al. [7]	<p>Poststroke participants</p> <ul style="list-style-type: none"> • $n = 3$ (1 F, 2 M) • Age: (55–61) years old • Time poststroke onset: (4–11) months • Hemiparetic side: left (3) • WMFT: 25–71 <p>Healthy control participants</p> <ul style="list-style-type: none"> • $n = 2$ 	<p>(1) Reaching movement from neutral position to non-specified location on a table.</p> <p>Seated subjects were asked to perform natural, self-paced reaching movement. All patients performed the reaching task with their hemiparetic arm and all normal subjects with their right arm.</p>	38
Jacquier-Bret et al. [19]	<p>Healthy participants</p> <ul style="list-style-type: none"> • $n = 11$ (1 F, 10 M) • Handedness: right-handed (11) 	<p>(1) Achieving a puzzle presented on the touch screen device.</p> <p>Task were performed by right UL. Subjects were seated against the back of a chair, in front of a touch screen device horizontally placed on a table, with the forearms resting on either side of the device. The center of the touch screen was at 15 cm from the edge of the table. Two sizes of devices, a 5 and a 10-in touch screen size, were used. For each device, two puzzles with a different number of pieces (9 or 16 pieces) were selected to manipulate the size of the piece of the puzzle. The size of the puzzle pieces is proportional to the screen size and inversely proportional to the number of pieces. Each of the four puzzles (9 or 16 pieces performed with a 5- or a 10-in touch screen) was repeated five times in a random order.</p>	53

F: Female; M: male; UL: upper limb; FMA: Fugl-Meyer Assessment; MAS: Modified Ashworth Scale; ROM: range of motion; ARAT: Action Research Arm Test; WMFT: Wolf Motor Function Test.

Table 2. Number of papers collected from PubMed and B-on.

Search terms	PubMed	B-on	References
“upper extremity” OR “upper limb” OR arm AND Kinematics OR motion OR movement AND Analysis OR assessment OR measurement	20	451	3

independent reviewers. From these, 86 were not included since they (1) studied sport gestures, passive movements, purposeless, or unclear movements; (2) and/or examined children, animals, corpses, or other pathologic conditions. From the 59 included articles, 45 were excluded as they (1) analyzed only one joint of the UL; (2) were in athletes; (3) used robots, exoskeletons, or virtual realities; (4) and/or were meta-analyses, reviews, case reports, pilot studies, technical notes, or studies published as conference proceedings.

A total of 14 articles were considered in the current review as shown in Figure 1, of which 4 included a healthy sample,^{12,17–19} 3 studied poststroke patients,^{10,20,21} and 7 comprised both a stroke group and a healthy/control group.^{7,9,11,22–25}

3.2 Collected information about samples

3.2.1 Samples including healthy participants (isolated and/or as a control)

From the articles comprising healthy participants, both singly and as a control group for poststroke patients, only one⁷ did not present demographic or any other information about these participants. All other 10 articles presented information about sex and 9 of them about age^{9,11,12,17,18,22–25} and handedness.^{9,11,12,17–19,22–24} Presence or clinical history of orthopedic or neurologic disorders that would affect UL performance were collected by authors of six articles.^{17–19,23–25} Few articles presented anthropometric information, namely height,^{11,17,18} weight,^{11,17,18} and body mass index (BMI),¹⁸ and even less checked UL range of motion,¹⁷ active shoulder elevation,²⁴ visual acuity,²⁴ and ability to follow verbal instructions.²⁴

Males were the most studied in six studies.^{9,11,12,19,22,24} A comparison of the kinematic metrics between both sexes was not found.

Five articles^{11,12,17,18,25} were performed with young adults, whose mean age ranged from 23.0 to 32.5 years old, and four articles^{9,22–24} included older participants, whose mean age ranged from 57.2 to 60.3 years old. A comparison of the kinematic metrics between age groups was not found.

The majority of the articles^{9,17–19,22–24} studied only right-handed subjects, and another two^{11,12} included mainly right-handed subjects. The latter did not analyze the kinematic metrics according to the handedness.

Of the studies that collected anthropometric data, only one¹¹ used this information to adjust and normalize the experimental set.

3.2.2 Samples including poststroke patients

A high variety of information had been collected by the authors of articles including poststroke patients. However,

just the age and the time poststroke onset were collected by all of them. The mean age ranged from 49.8¹¹ to 66.7²³ years old and most articles^{9,11,20,22–24} were carried out during the chronic phase (time after stroke onset ranging from 0.5 to 14.5 years). Two^{21,25} other articles analyze patients during the acute phase, one⁷ considered both subacute and chronic phases, and another one¹⁰ was performed during the subacute phase.

Other information gathered by most articles were sex,^{7,10,11,20–25} the “hemiparetic side,”^{7,10,11,21–25} the body function and structure through the Fugl-Meyer Assessment-Upper Extremity (FMA-UE),^{9–11,20,21,23–25} and previous history of stroke.^{9,10,20,21,24,25} Eight^{7,11,20–25} articles evaluated mostly males and the left side of body was the most “affected” in four articles^{10,21,23,24} (“hemiplegia side,” “hemiparetic side,” or “impaired arm function,” according to the authors). According to the FMA-UE, most authors included subjects with mild^{9–11,21,23–25} motor impairment. Nevertheless, five articles included also participants with severe,^{10,20,23–25} and moderate^{9,10,23–25} motor impairment. Only subjects with a single stroke were included in the studies that accounted this information.

In addition to FMA-UE, other clinical scales were used by some authors, namely the Ashworth Scale²² and its modified version,^{10,20,21} the Action Research Arm Test,^{10,21} the ABILHAND,¹⁰ the Motricity Index,²² the Brunnstrom Motor Recovery Stages,¹¹ and the Wolf Motor Function Test.⁷

Presence of problems that could affect the UL function or performance was checked by some authors, namely cognitive decline,^{11,20,23–25} sensory deficits,^{9,10,20–22} pain,^{9,10,20,21} other musculoskeletal or neurological conditions,^{9,10,21} visuospatial problems,^{22,24} and neglect.²⁵

Active^{20,23,24} and passive^{9,20,25} range of motion of UL joints as well as the ability to reach forward,²³ open the hand,²² grasp,²² and drink^{9,10} with the contralesional UL, at the assessment moment, were also gathered by some authors.

Kim et al.¹¹ were the only ones presenting information on height and weight, being the mean height 168 cm, and the mean weight 67.9 kg.

The articles that stated handedness of participants^{9,22,24} included only right-handed subjects.

About the stroke, five studies^{9,10,21,23,25} presented information about its type and only two about its side^{9,25} and location.^{23,25} Infarct (ischemic stroke) was the predominant stroke type.^{9,10,21,25} Murphy et al.⁹ studied subjects whose stroke side was mostly the right hemisphere and van Dokkum et al.²⁵ whose stroke side was mostly the left. The articles reporting stroke location used different categories: Patterson et al.²³ categorized according to the vascular territory and most of the participants had a stroke involving the middle cerebral artery; and van Dokkum et al.²⁵ grouped into “superficial/cortical,” “deep/subcortical,” and “superficial + deep” location categories and most of participants had a “deep/subcortical” or “superficial + deep” stroke. No articles have compared kinematic metrics according to stroke location.

Thrombolysis²¹ and imaging to confirm stroke²⁰ were only referred by one article. No study presented information about stroke severity or subtype, as well as about active hand movement and ability to walk independently at stroke onset.

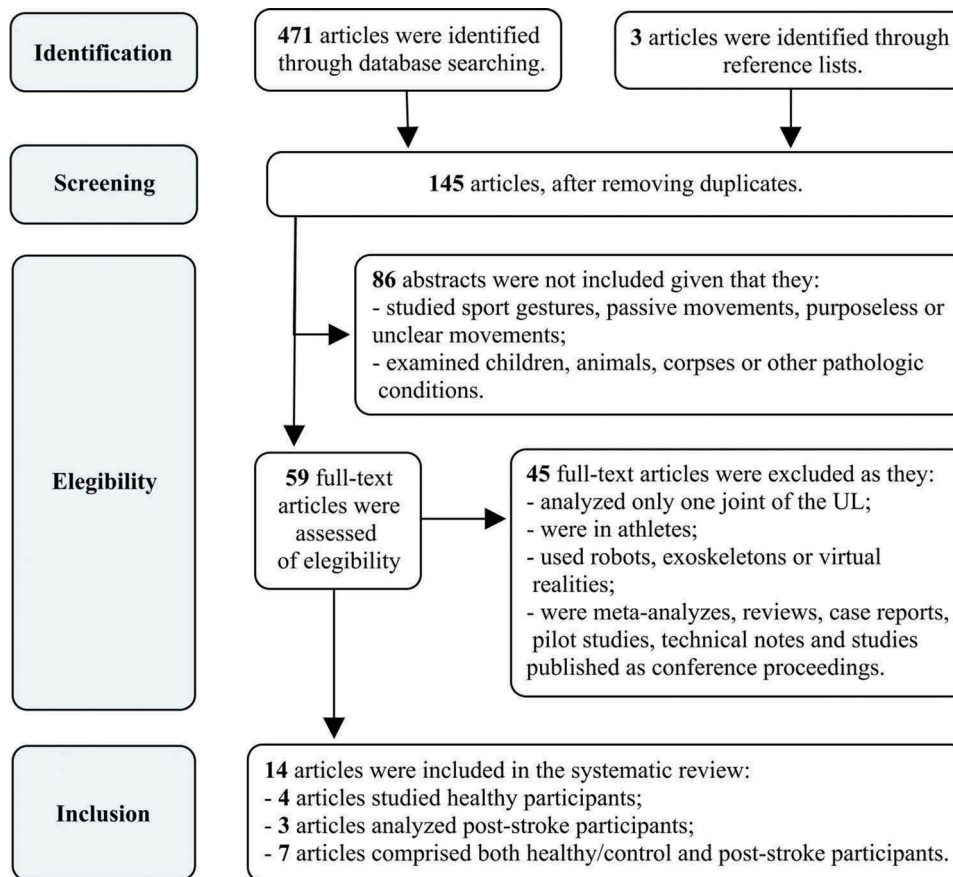


Figure 1. Review selection and exclusion criteria.

3.3 Motor tasks

Reviewers included only real ADL in the “ADL” category. Simulations of ADL were considered “functional movements” since they consist of reaching and touching body parts. “Achieving a puzzle presented on the touch screen device”¹⁹ was included in the “ADL” category, since interaction with technological devices is increasingly common in daily life.

Eight articles^{7,12,17,18,20,23–25} analyzed “functional movements,” being reach and touch a body part, namely the own mouth and forehead, the most accomplished.^{12,17,18}

Seven articles^{9–11,18,19,21,22} analyzed “ADL,” specifically tasks related to feeding^{9–11,18,21,22} and handling, transporting, and dropping objects of everyday life.^{18,19,22} Within these sub-categories, the most performed task was drinking.^{9–11,18,21,22}

Motor tasks were performed by only one UL in most articles^{7,11,12,17,19–23} (the “affected arm”^{7,20–22} in stroke participants, and the “corresponding” or the right^{7,12,19} UL in healthy/control participants); six articles^{9,10,18,22,24,25} evaluated both ULs. Only Thies et al.²² analyzed a bilateral motor task (“moving a plate”).

4. Discussion

In this systematic review, we gathered literature that analyzed the kinematics of ULs in order to identify which were (1) the information, and its characteristics, about stroke and healthy/control samples that was being collected, and (2) the motor

tasks/movement categories performed in these same articles. In fact, this information is extremely important as it guides the evidence serving as a basis for stroke rehabilitation and research. Beyond the answers found, this systematic review triggers a reflection on relevant elements to be considered in future studies.

4.1 Collected information about samples

Recently, SRRR recommendations for demographic and stroke information collection were published.³ Better knowledge of patients’ profiles not only will help to design better trials in terms of adequate stratification but also will generate new and better hypotheses about how therapies work and the underlying mechanisms of recovery.³ Age, sex, ethnicity, medical history, premorbid function, education, premorbid walking status, and premorbid living arrangements are the recommended demographic information.³ “Baseline” stroke severity (through the NIHSS), active hand movement and ability to walk independently at stroke onset, stroke type, subtype (lacunar/large artery/carotid dissection/undetermined) and location, as well as thrombolysis/reperfusion therapy and imaging are the recommended stroke information.³

About demographic information, only age and sex were accounted by almost all articles included in this review. Some of them also collected medical history. No further recommended demographic information was collected. With respect to their characteristics, most articles with

healthy participants presented subjects generally younger than those belonging to poststroke groups. For example, Kim et al.¹¹ excluded elderly from their healthy-control group “because they showed many neurological problems” (although they did not describe which) and because their study “aimed to build a database of more conventional motions of fine hand movements (...) and to compare differences from the hemiplegic group more accurately.” Considering the mean age found in this review for poststroke human adults (ranging from 49.8¹¹ to 66.7²³ years old) and the findings of another systematic review²⁶ (mean age of 68.6 years old among men, and 72.9 years among women), should we be using data from healthy young subjects as a reference/control of poststroke subjects, who are substantially older? Evidence shows that there are changes in postural control and mobility skills, namely in reaching movement time^{27,28} and coordination,^{29–32} with aging.³³ Is it reasonable that the reference for the rehabilitation of poststroke subjects comes from healthy young subjects? Do poststroke patients and health professionals intend to achieve a younger adult movement pattern? Taking this as a limitation, we state that studies are needed with healthy older adults analyzing differences between aging subgroups, to build an accurate database of more conventional UL movements and to study the best reference for the rehabilitation of poststroke patients.

Males were the most studied among both healthy and/or poststroke human adults. This finding is in agreement with the fact that stroke is more common among men, although the difference tends to decrease with age.²⁶ Nevertheless, stroke is usually more severe in women²⁶ and both genders have distinct morphological and functional features, which often determine the execution of different personal and professional activities. Therefore, we consider that future studies should compare their ULs kinematic metrics.

It is noteworthy that Murphy et al.¹⁰ were the only ones analyzing the influence of age and sex variables in regression models, but no significant influence was found.

Presence of chronic diseases, social and lifestyle factors, psychological, cognitive, and physical factors may impact poststroke recovery trajectories,³ as well as affect the reliability of “healthy”/control groups. For example, from the standing position, subjects with distinct BMI are expected to show variability of muscle activations of the trunk, namely in the core stability,³⁴ and ULs, influencing the performance of these segments.³⁵ However, few articles included in this review gave importance to anthropometric information. Only in the study of Kim et al.,¹¹ the sitting and table heights were adapted to obtain the same starting position for all participants, whereas other articles^{10,20,21} considered the UL’s length to adjust target location. Few articles described also poststroke human adults’ handedness and the articles including right- and left-handed subjects did not analyze the kinematic metrics according to it. Nevertheless, differences in the functional organization of motor areas in right- and left-handed people are known, specifically in sequential movements.³⁶ Therefore, although the impact of BMI, handedness, and other factors is not yet entirely clear, it is recommended that all studies collect this type of information to optimize stratification.³

Concerning the stroke information, no study presented information about initial stroke severity or subtype, as well as about active hand movement and ability to walk independently at stroke onset. According to SRRR recommendations,³ initial stroke severity (through the NIHSS) is one of the core measures to include in all trials, regardless of when the trial starts. Actually, initial stroke severity and age are the strongest predictors of outcome after acute stroke,³ which makes them an indispensable information to patients’ stratification and also to obtain valid results and conclusions. Individual item and total NIHSS scores should be reported in future studies.³ Active hand movement and walking at admission are recommended particularly in trials that begin later poststroke where NIHSS at stroke onset could not be gathered.³

Another recommended core measure is the FMA.³ Most authors used the FMA-UE to measure UL motor impairment and included subjects with *mild-to-severe* motor impairment. Murphy et al.⁹ found significant differences between poststroke participants with moderate versus mild UL impairment in the measures of compensatory trunk and UL movements, which is in accordance with other literature.^{37,38} van Dokkum et al.²⁵ also found a significant association between the FMA score and the number of velocity peaks of the “paretic” hand. Therefore, future studies should consider the severity level of motor impairment as an important factor for stratification.

Surprisingly, only two articles^{23,25} indicated the stroke location, whereas the stroke type was reported by several articles.^{9,10,21,23,25} The lesion location is generally assumed to be associated with the specificity of deficits.³⁹ Furthermore, recent data suggest that the site of ischemic penumbra could predict outcome or treatment response and affect motor recovery.⁴⁰ Therefore, future studies should analyze kinematically the impact of stroke location on UL motor function. To report stroke location and make easier comparisons between studies, the SRRR recommended the following categorization: cortical (internal capsule/middle cerebral artery/frontal lobe), subcortical (thalamus/basal ganglia), midbrain (pons/medulla/cerebellum), and brainstem.³

Curiously, many more articles have gathered information about the “hemiparetic” (“hemiplegic,” “affected,” or “impaired”) side (of the body), rather than the stroke side. Nevertheless, considering the commitment of both ULs after stroke and the recommendations for a bilateral (or global) intervention,^{24,41,42} the terms “contralesional” and “ipsilesional” should be adopted and the ipsilesional UL should be included in kinematic analysis. Only Finley et al.²⁴ considered the ipsilesional UL as “less affected.”

Thrombolysis²¹ and imaging to confirm stroke²⁰ were accounted by one article. Other recent SRRR consensus about biomarkers of stroke recovery⁴³ highlights the ascendant role that neuroimaging measures need to play in clinical decision-making for poststroke rehabilitation, namely as a measure of molecular/cellular processes that may be difficult to measure directly in humans. Consequently, future studies should collect information about stroke confirmation on imaging and obtainment of computed tomography and magnetic resonance imaging, as recommended.³

Contrariwise, all articles presented the time poststroke onset. Most of the articles analyzed poststroke human adults

in the chronic phase, however, with an unequal evolution time (from 0.5 up to 14.5 years). Although most poststroke changes occur until the chronic phase,³⁹ neuromuscular adaptations and modifications of the movement pattern may continue to happen, according to the sensorimotor experiences. Therefore, subjects with distinct evolution times after stroke should not be studied as similar. It is also recommended³ that future studies should also analyze UL movement in the acute phase, since at this time motor deficits result mainly from injury instead of possible compensatory control by alternative neural paths.^{44,45} This knowledge could provide a theoretical framework to create valid and advanced guidelines for the UL neurorehabilitation,^{45,46} implemented as soon as possible during the acute phase, empowering recovery of the affected function.

4.2 Motor tasks

Most articles^{7,12,17,18,20,23–25} analyzed “functional movements,” being reach and touch a body part, the most accomplished.^{12,17,18} According to their authors, these movements simulate ADL, related, for example, to personal care and hygiene.¹⁸ In addition, in two articles,^{12,17} “subjects were asked to copy¹² or to follow¹⁷ the movements of the instructor standing in front of them,” which may affect the execution of participants’ natural movement and the validity of these studies. Since movement varies according to the purpose and constraints of the task,³³ simulations of ADL or excessive instructions related to movement performance should be avoided. For this reason, we did not consider these simulations real “ADL.” To increase their validity, future studies should focus on real and daily life purpose tasks. Half of the articles included in this review do so, and most of them analyzed the “drinking” task. This seems to be a rich task for kinematic analysis of the UL as it includes subtasks such as reaching, grasping, transporting, and manipulating an object,³³ which makes possible the study of these different motor skills. However, it may become too complex for individuals with moderate or severe impairment, which could decrease the amount of participants in these studies. Therefore, simpler ADL are needed to include also subjects with more severe impairment and increase samples. We suggest a task involving just reaching without grasping, e.g. turning on the light.





In summary, the present systematic review identified the collected information and its characteristics about poststroke and healthy/control human adults that are being studied for ULs’ kinematics analysis, and the motor tasks performed in those same studies: age and sex were accounted by almost all articles and some of them also collected medical history; most samples were composed mainly by males, had a low mean age and their anthropometric characteristics were unknown; no study presented information about initial stroke severity or subtype, as well as about active hand movement and ability to walk independently at stroke onset; most authors used the FMA-UE to measure UL motor impairment and included subjects with different levels of motor impairment; few articles identified handedness of poststroke adults and stroke

location, whereas the stroke type was reported by several articles; more articles have gathered information about the “hemiparetic” side, rather than the stroke side; thrombolysis and imaging were accounted by one article; all articles presented the time poststroke onset and most of them analyzed poststroke adults in the chronic phase, whose time interval varied greatly; most articles analyzed just one UL and “functional movements,” namely ADL simulations. Some gaps were identified in most of the articles reviewed, which may compromise the creation of valid databases of the kinematics of ULs. Therefore, we suggest that future research (1) analyze the influence of sex and age on the kinematics of ULs; (2) identify anthropometric characteristics and adjust task environment to them; (3) report initial stroke severity, location, and side and consider these factors to patients’ stratification; (4) study poststroke human adults in the acute phase; (5) include ipsilesional UL in the analysis; and finally (6) select real ADL with greater and lesser complexity.

Conflict of Interest Statement

The authors report no conflicts of interest.

ORCID

Inês Albuquerque Mesquita  <http://orcid.org/0000-0001-9659-7531>
 Ana Rita Vieira Pinheiro  <http://orcid.org/0000-0003-4310-7652>
 Miguel Fernando Paiva Velhote Correia  <http://orcid.org/0000-0001-6065-9358>
 Cláudia Isabel Costa da Silva  <http://orcid.org/0000-0002-1484-1893>

References

- Walker MF, Hoffmann TC, Brady MC, et al. Improving the development, monitoring and reporting of stroke rehabilitation research: consensus-based core recommendations from the stroke recovery and rehabilitation roundtable. *Int J Stroke*. 2017;12(5):472–479. doi:10.1177/1747493017711815.
- Cramer SC, Nelles G, Benson RR, et al. A functional MRI study of subjects recovered from hemiparetic stroke. *Stroke*. 1997;28(12):2518–2527.
- Kwakkel G, Lannin NA, Borschmann K, et al. Standardized measurement of sensorimotor recovery in stroke trials: consensus-based core recommendations from the stroke recovery and rehabilitation roundtable. *Int J Stroke*. 2017;12(5):451–461. doi:10.1177/1747493017711813.
- Bernhardt J, Borschmann K, Boyd L, et al. Moving rehabilitation research forward: developing consensus statements for rehabilitation and recovery research. *Int J Stroke*. 2016;11(4):454–458. doi:10.1177/1747493016643851.
- de Los Reyes-Guzmán A, Dimbwadyo-Terrer I, Trincado-Alonso F, Monasterio-Huelin F, Torricelli D, Gil-Agudo A. Quantitative assessment based on kinematic measures of functional impairments during upper extremity movements: a review. *Clin Biomech*. 2014;29(7):719–727. doi:10.1016/j.clinbiomech.2014.06.013.
- Rutherford DJ, Kozey CH. Three-dimensional motion analysis: relevant concepts in physiotherapy movement dysfunction management. *J Nov Physiother*. 2014;4(214): doi: 10.4172/2165-7025.1000214.
- Ozturk A, Tartar A, Huseyinsinoglu BE, Ertas AH. A clinically feasible kinematic assessment method of upper extremity motor function impairment after stroke. *Meas*. 2016;80:207–216. doi:10.1016/j.measurement.2015.11.026.
- van Tuijl JH, Janssen-Potten YJ, Seelen HA. Evaluation of upper extremity motor function tests in tetraplegics. *Spinal Cord*. 2002;40:51–64.

9. Murphy MA, Willén KS, Sunnerhagen KS. Kinematic variables quantifying upper extremity performance after stroke during reaching and drinking from a glass. *Neurorehabil Neural Repair*. 2011;25(1):71–80. doi:10.1177/1545968310370748.
10. Murphy MA, Willén C, Sunnerhagen KS. Movement kinematics during drinking task are associated with the activity capacity level after stroke. *Neurorehabil Neural Repair*. 2012;26(9):1106–1115. doi:10.1177/1545968312448234.
11. Kim K, Song WK, Lee J, et al. Kinematic analysis of upper extremity movement during drinking in hemiplegic subjects. *Clin Biomech*. 2014;29(3):248–256. doi:10.1016/j.clinbiomech.2013.12.013.
12. van Andel CJ, Wolterbeek N, Doorenbosch CA, Veeger DH, Harlaar J. Complete 3D kinematics of upper extremity functional tasks. *Gait Posture*. 2008;27(1):120–127. doi:10.1016/j.gaitpost.2007.03.002.
13. Nowak DA. The impact of stroke on the performance of grasping: usefulness of kinetic and kinematic motion analysis. *Neurosci Biobehav Rev*. 2008;32(8):1439–1450. doi:10.1016/j.neubiorev.2008.05.021.
14. Moher D, Liberati A, Tetzlaff J, Altman DG, Group P. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Ann Intern Med*. 2009;151(4):264–269. W264.
15. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *J Epidemiol Community Health*. 1998;52:377–384.
16. West S, King V, Carey TS, et al. *Systems to Rate the Strength of Scientific Evidence*. Rockville, MD: Agency for Healthcare Research and Quality: AHRQ Publication No. 02-E016; 2002.
17. Chen W, Xiong C, Huang X, Sun R, Xiong Y. Kinematic analysis and dexterity evaluation of upper extremity in activities of daily living. *Gait Posture*. 2010;32(4):475–481. doi:10.1016/j.gaitpost.2010.07.005.
18. Aizawa J, Masuda T, Koyama T, et al. Three-dimensional motion of the upper extremity joints during various activities of daily living. *J Biomech*. 2010;43(15):2915–2922. doi:10.1016/j.jbiomech.2010.07.006.
19. Jacquier-Bret J, Gorce P, Motti Lilian G, Vigouroux N. Biomechanical analysis of upper limb during the use of touch screen: motion strategies identification. *Ergonomics*. 2017;60(3):358–365. doi:10.1080/00140139.2016.1175671.
20. Wagner JM, Rhodes JA, Patten C. Reproducibility and minimal detectable change of three-dimensional kinematic analysis of reaching tasks in people with hemiparesis after stroke. *Phys Ther*. 2008;88(5):652–663. doi:10.2522/ptj.20070255.
21. Murphy MA, Willén C, Sunnerhagen KS. Responsiveness of upper extremity kinematic measures and clinical improvement during the first three months after stroke. *Neurorehabil Neural Repair*. 2013;27:844–853. doi:10.1177/1545968313491008.
22. Thies SB, Tresadern PA, Kenney LP, et al. Movement variability in stroke patients and controls performing two upper limb functional tasks: a new assessment methodology. *J Neuroeng Rehabil*. 2009;6(2). doi:10.1186/1743-0003-6-2.
23. Patterson TS, Bishop MD, McGuirk TE, Sethi A, Richards LG. Reliability of upper extremity kinematics while performing different tasks in individuals with stroke. *J Mot Behav*. 2011;43(2):121–130. doi:10.1080/00222895.2010.548422.
24. Finley M, Combs S, Carnahan K, Peacock S, Van Buskirk A. Comparison of “less affected limb” reaching kinematics in individuals with chronic stroke and healthy age-matched controls. *Phys Occup Ther Geriatrics*. 2012;30(3):245–259. doi:10.3109/02703181.2012.716506.
25. van Dokkum L, Hauret I, Mottet D, Froger J, Métrot J, Laffont I. The contribution of kinematics in the assessment of upper limb motor recovery early after stroke. *Neurorehabil Neural Repair*. 2014;28(1):4–12. doi:10.1177/1545968313498514.
26. Appelros P, Stegmayr B, Terént A. Sex differences in stroke epidemiology: a systematic review. *Stroke*. 2009;40(4):1082–1090. doi:10.1161/STROKEAHA.108.540781.
27. Welford A. Motor skills and aging. In: Mortimer JPF, Maletta G, eds. *The Aging Motor System*. New York: Praeger; 1982:152–187.
28. Williams H. Aging and eye-coordination. In: Bard CFM, Hay L, eds. *Development of Eye-Hand Coordination across the Lifespan*. Columbia: University of South Carolina; 1990:327–357.
29. Fradet L, Lee G, Dounskaia N. Origins of submovements in movements of elderly adults. *J Neuroeng Rehabil*. 2008;5(1):28. doi:10.1186/1743-0003-5-28.
30. Pohl PS, Winstein CJ, Fisher BE. The locus of age-related movement slowing: sensory processing in continuous goal-directed aiming. *J Gerontol B Psychol Sci Soc Sci*. 1996;51:P94–102.
31. Morgan M, Phillips JG, Bradshaw JL, Mattingley JB, Ianssek R, Bradshaw JA. Age-related motor slowness: simply strategic? *J Gerontol*. 1994;49:M133–139.
32. Vrtunski PB, Patterson MB. Psychomotor decline can be described by discontinuities in response trajectories. *Int J Neurosci*. 1985;27:265–275.
33. Shumway-Cook A, Woollacott MH. *Motor Control: Translating Research into Clinical Practice*. 5th. ed Philadelphia, PA, London: Lippincott Williams & Wilkins; 2017.
34. AlAbdulwahab SS, Kachanathu SJ. Effects of body mass index on foot posture alignment and core stability in a healthy adult population. *J Exerc Rehabil*. 2016;12(3):182–187. doi:10.12965/jer.1632600.300.
35. Berrigan F, Simoneau M, Tremblay A, Hue O, Teasdale N. Influence of obesity on accurate and rapid arm movement performed from a standing posture. *Int J Obes (Lond)*. 2006;30(12):1750–1757. doi:10.1038/sj.ijo.0803342.
36. Solodkin A, Hlustik P, Dc N, Sl S. Lateralization of motor circuits and handedness during finger movements. *Eur J Neurol*. 2001;8:425–434.
37. Cirstea MC, Levin MF. Compensatory strategies for reaching in stroke. *Brain*. 2000;123:940–953.
38. Levin MF. Interjoint coordination during pointing movements is disrupted in spastic hemiparesis. *Brain*. 1996;119:281–293.
39. Nudo RJ. Recovery after brain injury: mechanisms and principles. *Front Hum Neurosci*. 2013;7:887. doi:10.3389/fnhum.2013.00887.
40. Rosso C, Samson Y. The ischemic penumbra: the location rather than the volume of recovery determines outcome. *Curr Opin Neurol*. 2014;27(1):35–41. doi:10.1097/WCO.0000000000000047.
41. Meskers CG, Koppe PA, Konijnenbelt MH, Veeger DH, Janssen TW. Kinematic alterations in the ipsilateral shoulder of patients with hemiplegia due to stroke. *Am J Phys Med Rehabil*. 2005;84:97–105.
42. Nakamura T, Abreu BC, Patterson RM, Buford WL, Ottenbacher KJ. Upper-limb kinematics of the presumed-to-be-unaffected side after brain injury. *Am J Occup Ther*. 2008;62:46–50.
43. Boyd LA, Hayward KS, Ward NS, et al. Biomarkers of stroke recovery: consensus-based core recommendations from the stroke recovery and rehabilitation roundtable. *Int J Stroke*. 2017;12(5):480–493. doi:10.1177/1747493017714176.
44. Lang CE, Wagner JM, Bastian AJ, et al. Deficits in grasp versus reach during acute hemiparesis. *Exp Brain Res*. 2005;166(1):126–136. doi:10.1007/s00221-005-2350-6.
45. Wagner JM, Lang CE, Sahrman SA, et al. Relationships between sensorimotor impairments and reaching deficits in acute hemiparesis. *Neurorehabil Neural Repair*. 2006;20(3):406–416. doi:10.1177/1545968306286957.
46. Wagner JM, Lang CE, Sahrman SA, Edwards DF, Dromerick AW. Sensorimotor impairments and reaching performance in subjects with poststroke hemiparesis during the first few months of recovery. *Phys Ther*. 2007;87(6):751–765. doi:10.2522/ptj.20060135.