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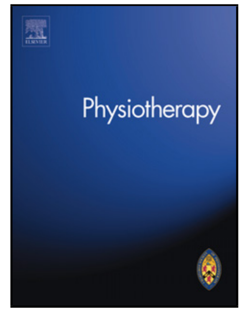

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Authors: Kathryn C. Collins, Niamh C. Kennedy, Allan Clark, Valerie M. Pomeroy

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Getting a kinematic handle on reach-to-grasp: A meta-analysis

Authors:

Kathryn C Collins [a], MSPT, NCS, Kathryn.collins@uea.ac.uk

Niamh C Kennedy [a,c] PhD, n.kennedy@ulster.ac.uk

Allan Clark [b], PhD, allan.clark@uea.ac.uk

Valerie M Pomeroy [a], PhD v.pomeroy@uea.ac.uk

[a] Acquired Brain Injury Rehabilitation Alliance, University of East Anglia, Norwich, NR4 7TJ, UK

[b] Norwich Medical School, University of East Anglia, Norwich, NR4 7TJ, UK

[c] School of Psychology, Ulster University, BT52 1SA

Corresponding Author:

Niamh Kennedy

Email: n.kennedy@ulster.ac.uk

Phone +44 02870123027

Postal address: Ulster University, Cromore Road, Coleraine, BT52 1SA

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Abstract

Background and Objectives

Reach-to-grasp is an essential everyday activity that is often impaired after stroke. The objectives of this review are: 1) identify differences in the kinematic characteristics of reach-to-grasp between individuals with and without stroke, and 2) determine the influence of object location on kinematics.

Data sources: MEDLINE, AMED, and Embase databases

Eligibility Criteria: Studies investigating individuals with stroke and neurologically intact control participants completing reach-to-grasp (paretic upper limb) of an object assessed via kinematic assessment (motion analysis).

Review Methods

Following Cochrane Collaboration guidelines a meta-analysis comparing kinematic characteristics of reach-to-grasp between individuals with and without stroke. Potential risk of bias was assessed using the Down's and Black Tool. Data were synthesised by calculating the standardised mean difference (SMD) in kinematic characteristics between adults with and without stroke.

Results

Twenty-nine studies met the review criteria, mainly of observational design; 460 individuals with stroke and 324 control participants. Kinematic differences in reach-to-grasp were identified in the central and ipsilateral workspace for example, individuals with stroke exhibited significantly lower peak velocity SMD -1.48 (95% CI -1.94, -1.02), and greater trunk displacement SMD 1.55 (95% CI 0.85, 2.25) than control participants. Included studies were assessed as demonstrating unclear or high potential risk-of-bias.

Conclusions

Differences in kinematic characteristics between individuals with and without stroke were identified which may be different reaching in the ipsilateral and central workspace. Suggesting, that object location may influence some kinematic characteristics and not others which may be pertinent when re-training reach-to-grasp.

Prospero Database Registration number: CRD42014009479

Contribution of the Paper

- Kinematic differences between individuals with stroke and control participants remain constant during reach-to-grasp in the central and ipsilateral workspace for velocity, movement time, elbow range of motion, trunk displacement. Object location may influence reach path ratio and smoothness of movement.
- Kinematic differences identified in this systematic review could be used for future investigation as targets of upper limb interventions to develop more specific interventions aimed at the underlying movement deficit.
- The reach-to-grasp literature is heterogeneous; future research investigating the standardisation of tasks and methods of data collection and analysis may ease direct comparisons between studies.

Key Words: reach-to-grasp, task performance and analysis, upper extremity, stroke, kinematics

Introduction

Stroke is the third leading cause of disability world-wide (1). There is evidence that physical therapy interventions improve upper limb function after stroke (2-4), but the optimal therapy to enhance upper limb motor recovery remains unknown (2). Identification of how to attain even better recovery is important as approximately 65% of individuals with stroke do not recover the ability to reach, grasp, and/or manipulate objects (5). This could be because the motor deficits resulting from stroke are heterogeneous (6). Therefore, therapy interventions may need to be targeted at the specific motor deficits experienced by individuals. An essential function of the upper limb is reach-to-grasp and part of almost all activities of daily living (ADL's). Successful reach-to-grasp requires temporal coordination of transport (reach) and grasp (7); it has been suggested that traditional therapy may not sufficiently target temporal coordination of the transport and grasp (2). A better understanding of the motor deficits in reach-to-grasp performance in individuals with stroke may enable interventions to be targeted at the underlying movement dysfunction which may lead to advances in therapy efficiency and functional outcomes.

It is established that successful reach-to-grasp is achieved through coordination of the nervous and the musculoskeletal systems (8, 9). The resultant movement performance can be quantitatively assessed using kinematic analysis providing sensitive, objective, and reliable measures of upper limb movement (8, 10-14). Essentially, kinematic analysis can enhance understanding of movement control through provision of objective data for parameters such as: movement speed; smoothness; trajectory; inter-segmental co-ordination; trunk displacement; and motion of individual joints which may then be used as targets for upper limb interventions. Such kinematic characteristics can impact an individual's ability to functionally use their arm for example, to complete activities of daily living. Additionally, these kinematic characteristics are part of a therapist's expert visual assessment of movement although maybe not captured by standardised outcome measures.

Narrative reviews have examined the biomechanics of reaching (8), coordination and neural control of reach-to-grasp (15), kinematic analysis of the upper limb during reaching (16), and the kinematics and cortical correlates of grasping (12). The narrative reviews have provided evidence that upper limb kinematics are changed following a stroke compared to control participants. However, the kinematic characteristics during reach-to-grasp have not yet been synthesized systematically. A systematic review and meta-analysis can provide a more robust evaluation of the of the literature though systematic and reproducible searching, evaluation of the evidence, and statistical combination of data (17).

When therapists develop/plan a reach-to-grasp intervention for individuals with stroke many factors are considered such as body positioning, object to be grasped, movement speed, trunk contribution, and object placement. It is of importance to understand how these factors may influence upper limb movement and kinematics which may aid in the refinement of the task. Furthermore, understanding the range of normal healthy upper limb movement can inform the understanding and identification of how movement is changed after stroke. The differences identified between individuals with stroke and healthy can be used to advance interventions targeted at the underlying movement deficits.

The aims of the systematic review reported here are to (1) determine if kinematic characteristics such as movement time, peak velocity, trunk contribution, smoothness of movement, reach path ratio, and elbow range of motion are different in individuals with stroke compared to control participants; and (2) determine the influence of task requirements such as object location; time since stroke and upper limb motor function on the kinematic differences (between individuals with stroke and control participants) during reach-to-grasp.

Methods

The methods of this systematic review are based on the guidelines provided by the Cochrane Collaboration (17); acknowledging the Cochrane guidelines were developed for randomised controlled trials and interventions.. However, the rigor of the Cochrane methodology was applied to the synthesis of observational studies in this review. Decisions about inclusion of studies, assessment of potential risk of bias, and extraction of data were made by two reviewers working independently. The two independent reviewers compared their results for consistency at each review stage. For any disagreements the two reviewers met and referred to the source documents. If agreement could not be reached then a third researcher was consulted. The protocol has been available on the Prospero database since June 5 2014 (CRD42014009479).

Search strategy

The search strategy was formulated in collaboration with a research librarian and included terms related to the upper limb, reach to grasp, kinematics, biomechanics, electromyography (EMG), transcranial magnetic stimulation (TMS), and movement analysis. The search strategy used within the MEDLINE database is provided in the supplementary online information (Table S1) as an example of how the terms were used. Because of differences between electronic databases the search strategy was modified for each one that was searched: MEDLINE, AMED, and EMBASE. Additionally, the reference lists of relevant papers were hand-searched to identify potential publications not already captured. Grey literature was not searched as it was important to ensure that included studies had undergone peer review prior to publication.

Each database was searched from its inception to 17 November 2015.

Eligibility Criteria

The search was limited to articles published in the English language.

Types of participants: Participants had to be at least 18 years of age. For individuals with stroke there were no limitations placed on stroke location, time since stroke or number of strokes. Control group participants needed to be free of any neurological or musculoskeletal disorder that may potentially influence movement control or kinematics of reach-to-grasp; hence forth referred to as control participants.

Types of studies: Prospective studies in which both individuals with stroke and control participants completed identical reach-to-grasp tasks were included. All study designs were included with the exception of single case studies due to lack of comparison between people with stroke and age-matched adults.

Types of reach-to-grasp task: The studies assessing reach-to-grasp; reach-to-grasp and lift; or reach-to-grasp and transport of an object using the paretic upper limb were included. Specific exclusion criteria included: reaching or pointing to a target, tapping, tracing, or drawing tasks, and reaching with the non-paretic limb.

Types of measures: Studies which employed the assessment of reach-to-grasp via kinematics (motion analysis) e.g. velocity; muscle activity (electromyography, EMG); or corticospinal pathway contribution (transcranial magnetic stimulation, TMS) during reach to grasp were included.

Identification of relevant studies

Two reviewers independently assessed potential studies for relevance based on the above pre-specified inclusion and exclusion criteria. Studies were assessed as not relevant, probably relevant, or relevant. Title and abstract were screened together. The full texts of those studies deemed as either relevant or probably relevant were then screened (17, 18).

Potential risk of bias

The Down's and Black Tool was used to assess the potential risk of bias (19) as the majority of relevant studies used observational designs. The Down's and Black Tool was designed for randomised controlled trials (RCT) and non-RCT studies; has reported reliability and validity (19); and has been used in previous systematic reviews of observational studies (20, 21). The tool was modified to be relevant to studies included in this review based on core criteria for assessing potential risk of bias (17, 22) (modified tool in: Supplemental Digital Content 1, Table S2). For example, questions relating to participant blinding, randomisation, group allocation, and group concealment were removed as they are not applicable to observational studies (20-22). Additionally, questions were modified such as “Is the reaching task clearly defined and reproducible” compared to a question regarding interventions (20-22). Two reviewers independently conducted the risk of bias assessment and compared their assessment for agreement. Any disagreements were resolved with reference to the full text paper. If agreement could not be reached then a third reviewer was consulted.

Data extraction

The data was extracted independently by two researchers using a standardised form: number of participants, age, time since stroke, reach-to-grasp task requirements, trunk restraint, upper limb motor ability, and kinematic characteristics (e.g. velocity). In intervention studies only the baseline (pre-intervention) data were extracted. The intervention studies included control participants as kinematic comparisons for individuals with stroke. For published papers in which the data were unclear or missing the authors were emailed requesting data clarification.

Synthesis

Meta-analysis was indicated when there were two or more studies which investigated a reach-to-grasp task in the same area of the workspace using a measure of the same kinematic characteristic. If meta-analysis was indicated it was conducted using the Cochrane Statistical package RevMan 5.2. If meta-analysis was not indicated a narrative synthesis was planned.

For meta-analysis the standardized mean difference (SMD) was calculated as extracted data were continuous (17); comparing group means and standard deviations of kinematic characteristics between individuals with stroke and control participants. The combination of observational studies within a meta-analysis has been done in earlier systematic reviews (23, 24) Heterogeneity of data was assessed using the I^2 statistic and categorised as low for a value of < 25%, high for a value of 75% or greater; and moderate for all values in between (17, 25, 26). If I^2 was ≤ 25% a fixed effect model was used, if I^2 was ≥ 26% a random effects model was used (17, 26).

If any one study contained multiple reach-to-grasp tasks such as reaching at different speeds then participants both individuals with stroke and healthy were divided between the different tasks within the meta-analysis to prevent double-counting and consequent potential bias in the findings (17). There were no study participants entered into a meta-analysis more than once. An additional step taken to minimise any potential bias was to perform a sensitivity analysis where it appeared that the same participants could have been included in separate papers reporting the same kinematic elements as different studies.   If a potential overlap of participants was suspected then, the meta-analysis was conducted with and without the studies under question as a sensitivity analysis.

Sensitivity analysis was also undertaken to assess the robustness of the results of the meta-analysis based on upper limb motor function and time since stroke (17, 27). Some studies reported separate outcomes for stroke survivors based on upper limb motor functional ability, such as moderate to severe disability versus mild disability, and time since stroke. Sensitivity analyses were also carried out excluding studies that did not age-match control participants as kinematic elements change from around age 50 (28, 29). Not all meta-analyses contained studies in which a sensitivity analysis could be conducted (separated participants based on time since stroke, upper limb motor function, or did not have age-matched controls); thus a sensitivity analysis was not carried out for every kinematic outcome.

Results

Relevant studies

The electronic database search identified 2,209 potential references, a further 74 references were identified from the reference list of relevant papers. Of these 2,283 references, 29 studies met the inclusion criteria and 27 were included in the meta-analysis. Full details are provided in the PRISMA flowchart, Figure 1.

Types of studies

The relevant studies included mostly observational study design (7, 13, 30-58) and two studies of experimental design (11, 59).

Participants

Reach-to-grasp was assessed with 460 individuals with stroke, and 324 control participants; participant characteristics for each included study are in the online Supplementary Table S3. In summary the mean age of individuals with stroke was 61(7) years (standard deviation, SD); and 56(10) years for control participants. Control participants were not consistently age-matched to individuals with stroke across included studies. The mean time of assessment post-stroke was 860 days (2.4 years) ranging from 2 days to 9.4 years after stroke.

Reach-to-grasp task

The reach-to-grasp tasks varied across all studies. Full details are in the online supplementary Table S3 and synthesised in Table 2. In summary, tasks included reach-to-grasp of an object (7, 13, 39, 50, 51), reach-to-grasp and lift of an object (31-33, 36, 37, 44, 55), and reach-to-grasp and transport of an object (11, 30, 34, 35, 38, 40-49, 52-54, 56-59). Task requirements also varied including the use of trunk restraint (31, 34, 35, 56-58) or no trunk restraint (13, 39-42, 46, 48, 50, 51, 59) during the task. Additionally, limb assessment of the control participants varied between studies assessing the dominant (13, 35, 37, 38, 48, 53, 54, 58, 59), non-dominant (34, 49, 57), or a mixture of both limbs (30, 32, 33, 42, 45, 46, 52, 55).

Outcome measures

The methods of data collection, data processing and analysis of kinematic characteristics investigated was varied across included studies. The most commonly assessed kinematic characteristics were: velocity (7, 13, 35, 36, 42, 45, 46, 48, 50-52, 54, 55, 57), movement time (7, 13, 30-33, 36-38, 41-47, 50, 52, 54, 55), movement smoothness (31, 45-47, 51), reach path ratio/trajectory (13, 32, 33, 35, 43, 48, 51, 55), joint range of motion (46, 48, 49, 51, 53, 54), and trunk contribution/displacement (13, 46, 48, 50, 53, 54).

Potential risk of bias

All included studies were assessed as having elements of unclear or high potential risk of bias, Table 3. The areas in which potential risk of bias were most evident were: reporting of adverse events; reporting of attrition; and blinding of assessors. Of relevance to this systematic review is the reproduction of the reach-to-grasp task and the description of the individuals with stroke to allow replication of the study and interpretation of the results; four studies demonstrated high or unclear potential risk of bias in these areas (11, 31, 45, 47).

Synthesis

Meta-analysis

Similar kinematic outcome measures were used in different studies. The kinematics for individuals with stroke were similar to each other and different to the control participants despite the varied reach-to-grasp tasks and research methods employed within the included studies.

The findings of the meta-analyses are summarised in Table 4 which provides the effect sizes, associated 95% CIs and direction of the difference between people with stroke and healthy adults. The Forest Plots for all kinematic outcomes are in Figures 2 to 7; the sensitivity analyses are in the online supplementary Figures S1-S16, a summary of the sensitivity analyses is in Table 5 providing the effect sizes, associated 95% Ci's and direction nof the difference between people with stroke and healthy adults. Heterogeneity was low I^2 (< 25%) for peak velocity ipsilateral, reach path ratio central, trunk displacement ipsilateral, and smoothness of movement central workspace. Heterogeneity was moderate (I^2 = 26-74%) for peak velocity central, movement time ipsilateral and central, trunk displacement central, and elbow ROM in the central workspace; heterogeneity was high for (I^2 > 75%) movement smoothness in the ipsilateral workspace.

Essentially, only two of the kinematic characteristics showed no difference between aindividuals with stroke and control participants namely: reach path ratio in the central workspace SMD 0.57 [95% CI -0.09, 1.23] p=1.00 and smoothness of movement in the ipsilateral workspace SMD 0.65 [95% CI -0.54, 1.85] p=0.02 (Table 4). All other kinematic characteristics such as peak velocity, movement time, trunk displacement, elbow range of motion, smoothness of movement (central workspace) and reach path ratio (ipsilateral workspace) were significantly different between individuals with stroke and control participants reaching in the central and ipsilateral workspace. Stroke survivors demonstrated longer movement times, lower peak velocity, greater trunk displacement, less elbow range of motion, more curved reach path, and less smooth movement. The results ranging from -1.48 [95% CI -1.94, -1.02] for peak velocity in the central workspace to 1.97 [95% CI 1.23, 2.72] for movement time in the central workspace (Table 4, Figures 2-7.).

Sensitivity analyses demonstrated no differences in the meta-analyses when removing individuals with mild stroke, moderate stroke, participants less than three months after stroke and studies that did not age-match control participants to the individuals with stroke with the exception of elbow range of motion. Excluding individuals with mild motor deficits and non-aged matched controls there were no differences in elbow range of motion between stroke survivors and healthy controls.. A summary of the sensitivity analyses are in Table 5, the forest plots are in Figures S1 to S16 in the online supplementary material.).

Discussion

The findings demonstrate that individuals with stroke exhibit significantly lower peak velocity, longer movement time, decreased smoothness (not ipsilateral workspace), increased curvature of reach path ratio (not central workspace), greater trunk displacement, and less elbow extension during reach-to-grasp compared to control participants (objectives 1 and 2). Thus, task requirements such as object location (e.g. ipsilateral workspace and distance from participant) may influence kinematic characteristics (objective 2). Different object locations will require different joint combinations and potentially different movement speeds which can impact on the reach path taken and the smoothness of movement. However, the primary studies were assessed as exhibiting unclear or high potential risk of bias, therefore the findings should be interpreted cautiously.

The potential risk of bias for studies included in this review were assessed as mostly unclear or high; it is accepted that observational study designs have greater potential risk of bias than randomized controlled trials (17). Of importance to this review and for study replication the reach-to-grasp task needs to be clearly defined as well as the group of individuals with stroke of which a majority of studies met the criteria. The potential risk of bias in included studies may be a possible limitation of the review.

Another possible limitation is that the search was restricted to studies published in the English language. Another source of publication bias could be that associated with the tendency for publication of studies with “positive” as opposed to “negative” findings. However, such bias against “negative” findings could be more evident in the reporting of randomised controlled trials than observational studies of the kinematics of movement. The possibility of reviewer bias was reduced because the search strategy was comprehensive and reviewers worked independently to identify relevant studies.

The findings of the present meta-analyses are in broad agreement with conclusions of earlier narrative reviews (8, 15, 16). For example, individuals with stroke exhibit lower peak velocities, longer movement times, and decreased smoothness of movement compared to control participants (8, 15, 16). However, earlier reviews combined the kinematics of reach-to-grasp and reach-to-target, (16) yet upper limb kinematics are different for different tasks (45, 60). The present systematic review therefore provides more specific information as well as objective data for more robust interpretation.

Interestingly, two meta-analyses did not demonstrate significant differences between individuals with stroke and control participants. First, reach path ratio in the central workspace, and second movement smoothness in the ipsilateral workspace. A potential explanation for the insignificant differences in reach path ratio is the specific joint combinations of the flexor synergy (40, 61) combined with the naturally more curved reach path to reach to the central workspace. For the second characteristic there were only two relevant studies. One demonstrating significant findings (31) the other non-significant findings (45). It is possible that the limited number of participants did not provide enough statistical power to determine a potential difference.

Another potential limitation may be the control participants were not consistently age-matched to the individuals with stroke. This is important as upper limb biomechanics changes from around age 50 (28, 29) and the average age of a stroke survivor is around 65 years (62). In addition to biomechanical changes there are also neurological changes such as: changes in white matter, interhemispheric connections via the corpus collusum, tissue density, myelination, and number of myelinated neurons within the corticospinal pathway (65,66) all of which can impact on upper limb motor control and thus kinematics. Comparing the kinematics of stroke survivors to younger adults may overestimate the differences found, potentially inducing bias in the findings.

Kinematics of the non-dominant upper limb differ to those of the dominant limb (63). The limb used by the control participants to complete the reach-to-grasp task varied in included studies some utilising the dominant limb (13, 35, 37, 38, 48, 53, 54, 58, 59), non-dominant limb (34, 49, 57), and others a mixture of both limbs (30, 32, 33, 42, 45, 46, 52, 55). Comparing the kinematic differences of the dominant limb may result in greater differences in kinematics and possibly contribute to potential bias in the meta-analyses.

The included studies were heterogeneous for: upper limb motor ability for individuals with stroke; time since stroke; task constraints; and methods of data collection and analysis. A possible limitation of the heterogeneity is the combination of varied studies (17); however, only one meta-analysis that demonstrated high heterogeneity ($I^2 > 75\%$) the remainder demonstrating low to moderate. On the other hand, heterogeneity can be viewed as a positive: the kinematic differences between individuals with and without stroke demonstrated consistent patterns despite variability in tasks and participants. However, we acknowledge that different samples of individuals with stroke between studies may complicate generalisability. It would be advisable to form a consensus on (a) which reach-to-grasp tasks most replicate ADL's and (b) standardisation methods of data collection and analysis. A standardised assessment of relevant reach-to-grasp tasks would contribute to more direct comparisons between studies increasing the clinical relevance of kinematic assessment to inform decisions on interventions.

A strength of the present meta-analyses is that the sensitivity analyses did not alter the results. One sensitivity analysis was based on evidence that individuals with stroke with moderate motor deficits demonstrate different kinematics to those with mild motor deficits (46, 48, 50, 52-54). However, the sensitivity analyses revealed that differences in kinematics between individuals with stroke and control participants remained constant when both individuals with mild stroke deficits and moderate stroke deficits were removed. Of note, the confidence intervals of individuals with moderate motor deficits were wider suggesting greater movement variability.

The second sensitivity analysis was based on the knowledge that early after stroke individuals are likely to be participating in rehabilitation, exhibit a more rapid rate of motor recovery (5), and over time with recovery kinematics change (59). Whereas, later after stroke individuals are less likely to be in rehabilitation and may have developed individual techniques or compensation (64). The sensitivity analysis found no differences in the kinematics when individuals less than three months after stroke were removed from analysis. Potential limitations to this interpretation are that: only three studies included separate data for people within three months after stroke and the studies measured different kinematic characteristics (11, 30, 35).

Clinical Implications and Conclusions

This meta-analysis shows that individuals with stroke perform reach-to-grasp tasks with lower peak velocity, longer movement time, decreased movement smoothness (not ipsilateral workspace), increased curvature of reach path ratio (not central workspace), greater trunk displacement and less elbow extension than control participants. All of these kinematic characteristics are therefore potential clinical targets for rehabilitation therapy. However, there was substantial potential risk of bias and heterogeneity of included studies thus definitive targets for rehabilitation interventions cannot be determined as yet.

Kinematic measurement provides valuable and meaningful information about upper limb movement control; of value for future research is identifying the minimal clinically important (MCID) difference. The MCID can provide functional relevance for stroke survivors as well as advance assessment and interpretation of longitudinal change in kinematics. Finally, development of standardised tasks and measurement may facilitate increased use of kinematic assessment in the clinical setting and improve comparisons between studies.

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Figure 1 Prisma diagram detailing the search and processes of identification of relevant of studies included in the systematic review.

Figure 1 Prisma Diagram

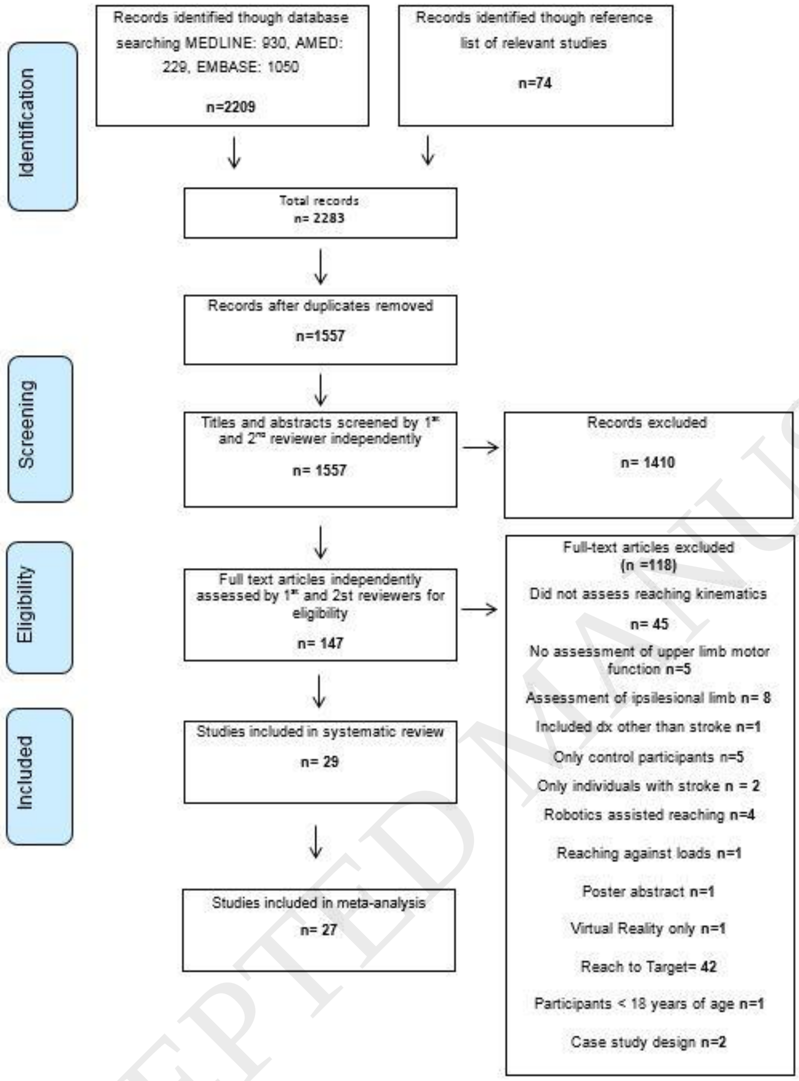

Figure 2 A, B, C Meta-analyses of SMD comparing peak velocity of individuals with stroke to control participants reaching in the central (A and B) and ipsilateral workspace (C). Studies with an * indicate potentially overlapping participants. The left side of the forest plot indicates lower peak velocity; the right side indicates higher peak velocity measured in mm/s. Individuals with stroke demonstrate significantly lower peak velocity in both the central and ipsilateral workspace. SMD=standardised mean difference

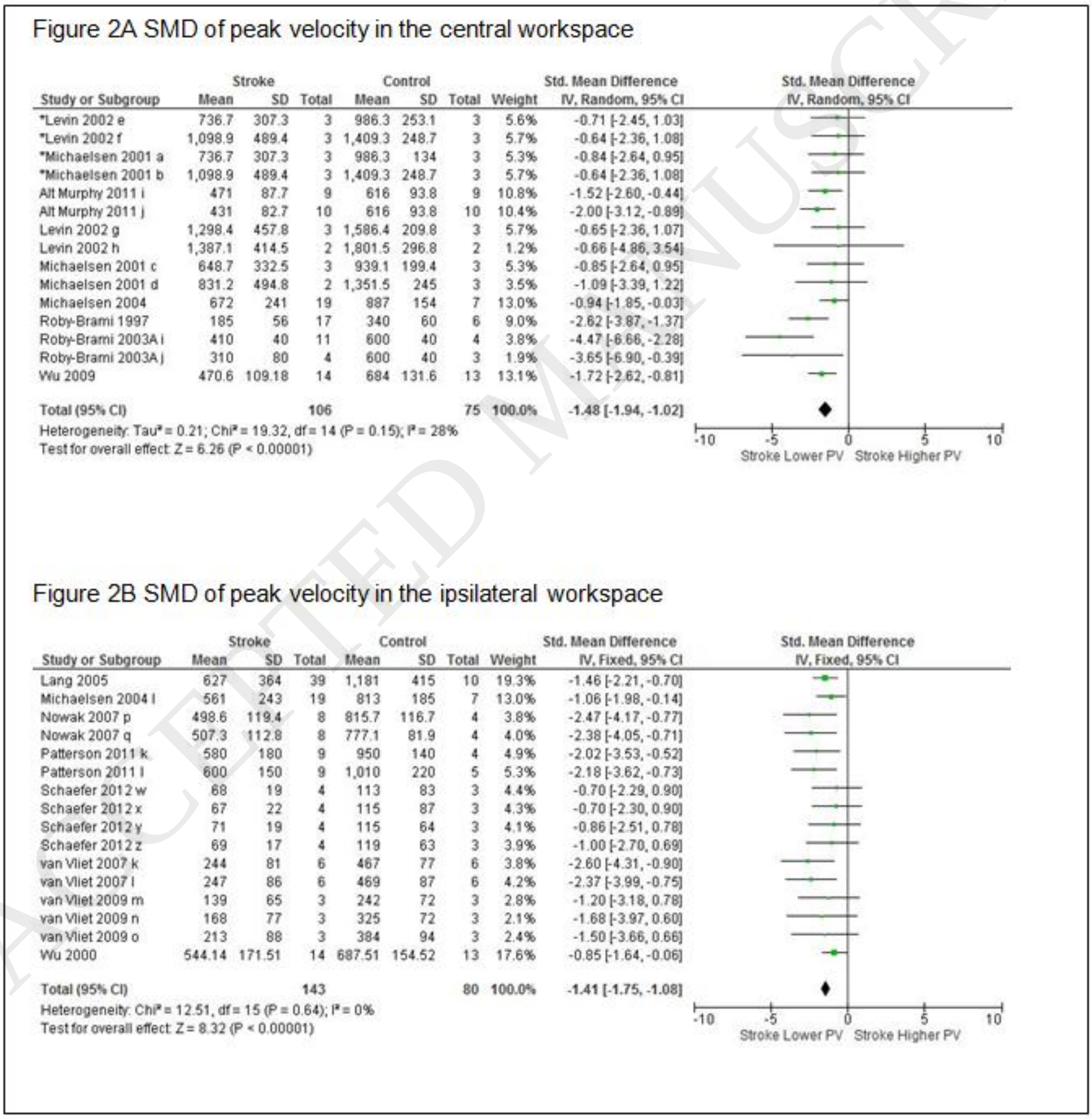

Figure 2A SMD of peak velocity in the central workspace

Study or Subgroup	Stroke Mean	Stroke SD	Stroke Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
*Levin 2002 e	736.7	307.3	3	986.3	253.1	3	5.6%	-0.71 [-2.45, 1.03]
*Levin 2002 f	1,098.9	489.4	3	1,409.3	248.7	3	5.7%	-0.64 [-2.36, 1.08]
*Michaelsen 2001 a	736.7	307.3	3	986.3	134	3	5.3%	-0.84 [-2.64, 0.95]
*Michaelsen 2001 b	1,098.9	489.4	3	1,409.3	248.7	3	5.7%	-0.64 [-2.36, 1.08]
Alt Murphy 2011 i	471	87.7	9	616	93.8	9	10.8%	-1.52 [-2.60, -0.44]
Alt Murphy 2011 j	431	82.7	10	616	93.8	10	10.4%	-2.00 [-3.12, -0.89]
Levin 2002 g	1,298.4	457.8	3	1,586.4	209.8	3	5.7%	-0.65 [-2.36, 1.07]
Levin 2002 h	1,387.1	414.5	2	1,801.5	296.8	2	1.2%	-0.66 [-4.86, 3.54]
Michaelsen 2001 c	648.7	332.5	3	939.1	199.4	3	5.3%	-0.85 [-2.64, 0.95]
Michaelsen 2001 d	831.2	494.8	2	1,351.5	245	3	3.5%	-1.09 [-3.39, 1.22]
Michaelsen 2004	672	241	19	887	154	7	13.0%	-0.94 [-1.85, -0.03]
Roby-Brami 1997	185	56	17	340	60	6	9.0%	-2.62 [-3.87, -1.37]
Roby-Brami 2003A i	410	40	11	600	40	4	3.8%	-4.47 [-6.66, -2.28]
Roby-Brami 2003A j	310	80	4	600	40	3	1.9%	-3.65 [-6.90, -0.39]
Wu 2009	470.6	109.18	14	684	131.6	13	13.1%	-1.72 [-2.62, -0.81]
Total (95% CI)			**106**			**75**	**100.0%**	**-1.48 [-1.94, -1.02]**

Heterogeneity: $Tau^2 = 0.21$; $Chi^2 = 19.32$, df = 14 (P = 0.15); $I^2 = 28\%$
Test for overall effect: Z = 6.26 (P < 0.00001)

Figure 2B SMD of peak velocity in the ipsilateral workspace

Study or Subgroup	Stroke Mean	Stroke SD	Stroke Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Lang 2005	627	364	39	1,181	415	10	19.3%	-1.46 [-2.21, -0.70]
Michaelsen 2004 l	561	243	19	813	185	7	13.0%	-1.06 [-1.98, -0.14]
Nowak 2007 p	498.6	119.4	8	815.7	116.7	4	3.8%	-2.47 [-4.17, -0.77]
Nowak 2007 q	507.3	112.8	8	777.1	81.9	4	4.0%	-2.38 [-4.05, -0.71]
Patterson 2011 k	580	180	9	950	140	4	4.9%	-2.02 [-3.53, -0.52]
Patterson 2011 l	600	150	9	1,010	220	5	5.3%	-2.18 [-3.62, -0.73]
Schaefer 2012 w	68	19	4	113	83	3	4.4%	-0.70 [-2.29, 0.90]
Schaefer 2012 x	67	22	4	115	87	3	4.3%	-0.70 [-2.30, 0.90]
Schaefer 2012 y	71	19	4	115	64	3	4.1%	-0.86 [-2.51, 0.78]
Schaefer 2012 z	69	17	4	119	63	3	3.9%	-1.00 [-2.70, 0.69]
van Vliet 2007 k	244	81	6	467	77	6	3.8%	-2.60 [-4.31, -0.90]
van Vliet 2007 l	247	86	6	469	87	6	4.2%	-2.37 [-3.99, -0.75]
van Vliet 2009 m	139	65	3	242	72	3	2.8%	-1.20 [-3.18, 0.78]
van Vliet 2009 n	168	77	3	325	72	3	2.1%	-1.68 [-3.97, 0.60]
van Vliet 2009 o	213	88	3	384	94	3	2.4%	-1.50 [-3.66, 0.66]
Wu 2000	544.14	171.51	14	687.51	154.52	13	17.6%	-0.85 [-1.64, -0.06]
Total (95% CI)			**143**			**80**	**100.0%**	**-1.41 [-1.75, -1.08]**

Heterogeneity: $Chi^2 = 12.51$, df = 15 (P = 0.64); $I^2 = 0\%$
Test for overall effect: Z = 8.32 (P < 0.00001)

Figure 3 A, B Forest Plots of the SMD of movement time during reach-to-grasp comparing individuals with stroke to control participants reaching in the central workspace (A) and ipsilateral workspace (B). A fixed effects model was used if $I^2 < 25\%$, a random effects model was used if $I^2 > 25\%$. The left side of the forest plot indicates shorter movement time, the right side of the plot indicates longer movement time measured in seconds. Individuals with stroke demonstrate significantly longer movement times during reach-to-grasp in both the central and ipsilateral workspace. SMD=standardised mean difference, MT= movement time

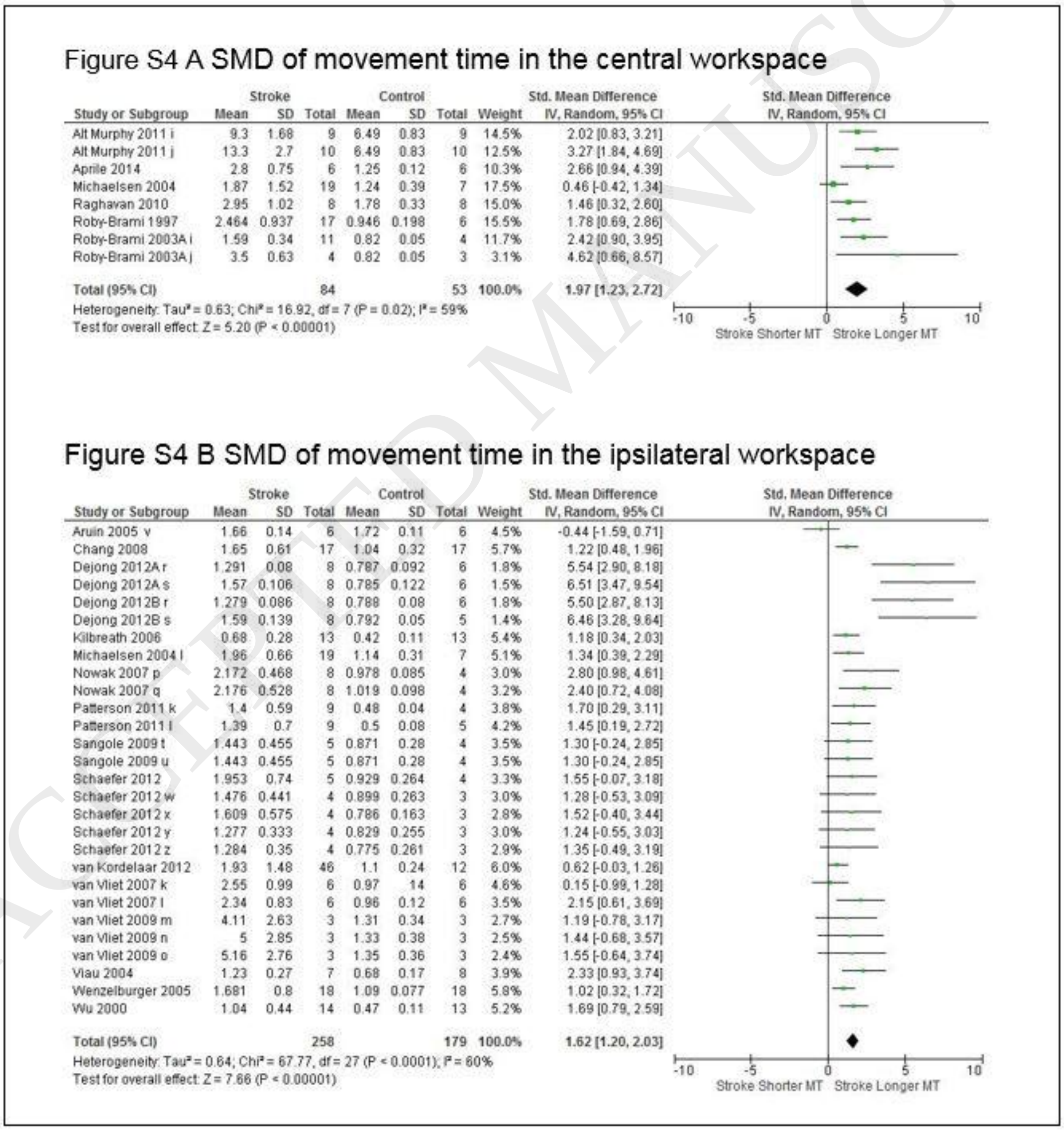

Figure S4 A SMD of movement time in the central workspace

Study or Subgroup	Stroke Mean	Stroke SD	Stroke Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Alt Murphy 2011 i	9.3	1.68	9	6.49	0.83	9	14.5%	2.02 [0.83, 3.21]
Alt Murphy 2011 j	13.3	2.7	10	6.49	0.83	10	12.5%	3.27 [1.84, 4.69]
Aprile 2014	2.8	0.75	6	1.25	0.12	6	10.3%	2.66 [0.94, 4.39]
Michaelsen 2004	1.87	1.52	19	1.24	0.39	7	17.5%	0.46 [-0.42, 1.34]
Raghavan 2010	2.95	1.02	8	1.78	0.33	8	15.0%	1.46 [0.32, 2.60]
Roby-Brami 1997	2.464	0.937	17	0.946	0.198	6	15.5%	1.78 [0.69, 2.86]
Roby-Brami 2003A i	1.59	0.34	11	0.82	0.05	4	11.7%	2.42 [0.90, 3.95]
Roby-Brami 2003A j	3.5	0.63	4	0.82	0.05	3	3.1%	4.62 [0.66, 8.57]
Total (95% CI)			**84**			**53**	**100.0%**	**1.97 [1.23, 2.72]**

Heterogeneity: $Tau^2 = 0.63$; $Chi^2 = 16.92$, $df = 7$ ($P = 0.02$); $I^2 = 59\%$
Test for overall effect: $Z = 5.20$ ($P < 0.00001$)

Figure S4 B SMD of movement time in the ipsilateral workspace

Study or Subgroup	Stroke Mean	Stroke SD	Stroke Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Aruin 2005 v	1.66	0.14	6	1.72	0.11	6	4.5%	-0.44 [-1.59, 0.71]
Chang 2008	1.65	0.61	17	1.04	0.32	17	5.7%	1.22 [0.48, 1.96]
Dejong 2012A r	1.291	0.08	8	0.787	0.092	6	1.8%	5.54 [2.90, 8.18]
Dejong 2012A s	1.57	0.106	8	0.785	0.122	6	1.5%	6.51 [3.47, 9.54]
Dejong 2012B r	1.279	0.086	8	0.788	0.08	6	1.8%	5.50 [2.87, 8.13]
Dejong 2012B s	1.59	0.139	8	0.792	0.05	5	1.4%	6.46 [3.28, 9.64]
Kilbreath 2006	0.68	0.28	13	0.42	0.11	13	5.4%	1.18 [0.34, 2.03]
Michaelsen 2004 l	1.96	0.66	19	1.14	0.31	7	5.1%	1.34 [0.39, 2.29]
Nowak 2007 p	2.172	0.468	8	0.978	0.085	4	3.0%	2.80 [0.98, 4.61]
Nowak 2007 q	2.176	0.528	8	1.019	0.098	4	3.2%	2.40 [0.72, 4.08]
Patterson 2011 k	1.4	0.59	9	0.48	0.04	4	3.8%	1.70 [0.29, 3.11]
Patterson 2011 l	1.39	0.7	9	0.5	0.08	5	4.2%	1.45 [0.19, 2.72]
Sangole 2009 t	1.443	0.455	5	0.871	0.28	4	3.5%	1.30 [-0.24, 2.85]
Sangole 2009 u	1.443	0.455	5	0.871	0.28	4	3.5%	1.30 [-0.24, 2.85]
Schaefer 2012	1.953	0.74	5	0.929	0.264	4	3.3%	1.55 [-0.07, 3.18]
Schaefer 2012 w	1.476	0.441	4	0.899	0.263	3	3.0%	1.28 [-0.53, 3.09]
Schaefer 2012 x	1.609	0.575	4	0.786	0.163	3	2.8%	1.52 [-0.40, 3.44]
Schaefer 2012 y	1.277	0.333	4	0.829	0.255	3	3.0%	1.24 [-0.55, 3.03]
Schaefer 2012 z	1.284	0.35	4	0.775	0.261	3	2.9%	1.35 [-0.49, 3.19]
van Kordelaar 2012	1.93	1.48	46	1.1	0.24	12	6.0%	0.62 [-0.03, 1.26]
van Vliet 2007 k	2.55	0.99	6	0.97	14	6	4.6%	0.15 [-0.99, 1.28]
van Vliet 2007 l	2.34	0.83	6	0.96	0.12	6	3.5%	2.15 [0.61, 3.69]
van Vliet 2009 m	4.11	2.63	3	1.31	0.34	3	2.7%	1.19 [-0.78, 3.17]
van Vliet 2009 n	5	2.85	3	1.33	0.38	3	2.5%	1.44 [-0.68, 3.57]
van Vliet 2009 o	5.16	2.76	3	1.35	0.36	3	2.4%	1.55 [-0.64, 3.74]
Viau 2004	1.23	0.27	7	0.68	0.17	8	3.9%	2.33 [0.93, 3.74]
Wenzelburger 2005	1.681	0.8	18	1.09	0.077	18	5.8%	1.02 [0.32, 1.72]
Wu 2000	1.04	0.44	14	0.47	0.11	13	5.2%	1.69 [0.79, 2.59]
Total (95% CI)			**258**			**179**	**100.0%**	**1.62 [1.20, 2.03]**

Heterogeneity: $Tau^2 = 0.64$; $Chi^2 = 67.77$, $df = 27$ ($P < 0.0001$); $I^2 = 60\%$
Test for overall effect: $Z = 7.66$ ($P < 0.00001$)

Figure 4 A, B, Forest plots of the SMD of the reach path ratio comparing individuals with stroke to control participants reaching in the central (A) and ipsilateral workspace (B). . A fixed effects model was used if $I^2 < 25\%$, a random effects model was used if $I^2 > 25\%$. The left of the forest plot indicates a straighter reach (exhibited by neurologically intact adults); the right side of the forest plot indicates a more curved reach path. Individuals with stroke demonstrate a more curved reach path compared to control participants, with significant differences in the ipsilateral workspace only. RPR=reach path ratio, SMD=standardised mean difference

reach path ratio

Figure 4A Reach Path Ratio Central Workspace

	Stroke			Control				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Fixed, 95% CI
*Levin 2002 e	1.8	0.52	3	1.54	0.13	3	15.4%	0.55 [-1.14, 2.23]
*Levin 2002 f	1.34	0.22	3	1.2	0.12	3	14.9%	0.63 [-1.08, 2.34]
*Michaelsen 2001 a	1.8	0.52	3	1.54	0.13	3	15.4%	0.55 [-1.14, 2.23]
*Michaelsen 2001 b	1.34	0.22	3	1.2	0.12	3	14.9%	0.63 [-1.08, 2.34]
Levin 2002 g	1.22	0.22	3	1.11	0.05	3	15.4%	0.55 [-1.14, 2.24]
Levin 2002 h	1.18	0.21	2	1.06	0.03	2	4.2%	0.46 [-2.79, 3.70]
Michaelsen 2001 c	1.88	0.59	3	1.55	0.17	3	15.1%	0.61 [-1.10, 2.31]
Michaelsen 2001 d	1.35	0.24	2	1.22	0.08	2	4.7%	0.42 [-2.64, 3.47]
Total (95% CI)			**22**			**22**	**100.0%**	**0.57 [-0.09, 1.23]**

Heterogeneity: $Chi^2 = 0.03$, $df = 7$ ($P = 1.00$); $I^2 = 0\%$
Test for overall effect: $Z = 1.70$ ($P = 0.09$)

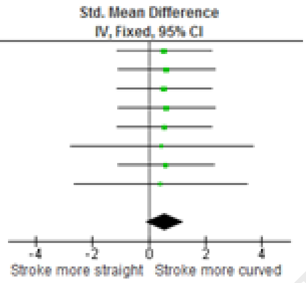

Figure 4 B Reach Path Ratio in the ipsilateral workspace

	Stroke			Control				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Dejong 2012A r	1.38	0.04	8	1.22	0.04	6	6.9%	3.74 [1.80, 5.69]
Dejong 2012A s	1.37	0.03	8	1.17	0.04	8	5.7%	5.35 [3.00, 7.70]
Dejong 2012B r	1.37	0.04	8	1.23	0.05	6	8.0%	2.95 [1.28, 4.62]
Dejong 2012B s	1.35	0.04	8	1.18	0.04	5	6.3%	3.95 [1.82, 6.09]
Lang 2005	2.16	1.68	39	1.08	0.07	10	12.1%	0.70 [-0.01, 1.41]
Patterson 2011 k	1.16	0.08	8	1.03	0.02	5	9.1%	1.86 [0.45, 3.27]
Patterson 2011 l	1.19	0.14	8	1.04	0.02	4	9.4%	1.18 [-0.15, 2.51]
Schaefer 2012 w	1.35	0.16	4	1.17	0.1	3	7.8%	1.09 [-0.64, 2.82]
Schaefer 2012 x	1.35	0.16	4	1.17	0.11	3	7.8%	1.07 [-0.65, 2.79]
Schaefer 2012 y	1.34	0.15	4	1.22	0.13	3	8.3%	0.71 [-0.89, 2.31]
Schaefer 2012 z	1.37	0.15	4	1.21	0.16	3	8.1%	0.87 [-0.78, 2.52]
Viau 2004	1.76	0.62	7	1.39	0.16	8	10.6%	0.80 [-0.27, 1.86]
Total (95% CI)			**110**			**64**	**100.0%**	**1.79 [1.06, 2.52]**

Heterogeneity: $Tau^2 = 1.01$; $Chi^2 = 32.05$, $df = 11$ ($P = 0.0007$); $I^2 = 66\%$
Test for overall effect: $Z = 4.82$ ($P < 0.00001$)

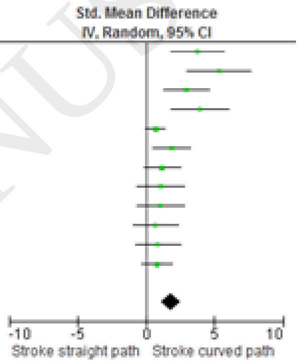

Figure 5 A, B. Forest plots of the SMD of trunk contribution/displacement during reach-to-grasp comparing individuals with stroke to control participants in the central (A) and ipsilateral workspace (B). A fixed effects model was used if $I^2 < 25\%$, a random effects model if $I^2 > 25\%$. The left side of the forest plot indicates less trunk movement (displacement) during reach-to-grasp, the right side indicates more trunk movement (displacement) during reach to grasp measured in mm. Individuals with stroke demonstrate significantly greater trunk displacement compared to control participants in both the central and ipsilateral workspace. SMD=standardised mean difference

Figure 5 A Trunk contribution central workspace

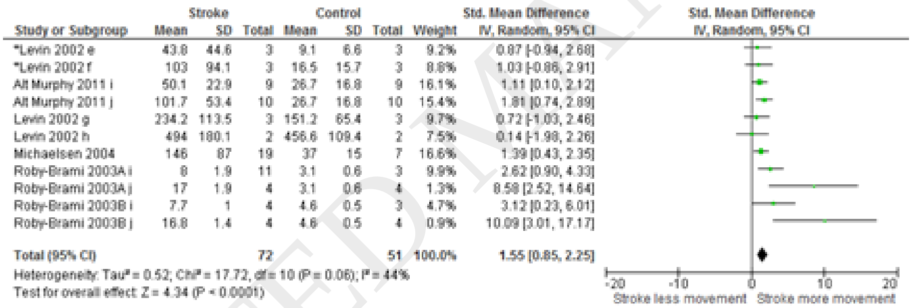

Figure 5 B Trunk contribution ipsilateral workspace

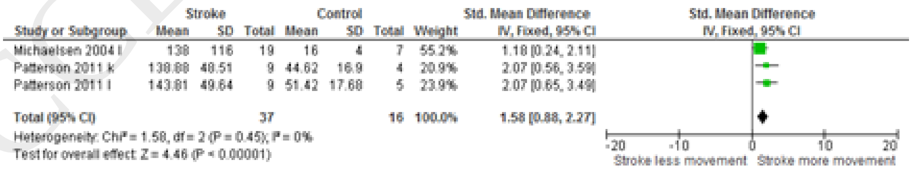

Figure 6 A, B - Forest plot of the SMD of movement smoothness during reach-to-grasp comparing individuals with stroke to control participants in the central (A) and ipsilateral workspace (B). A fixed effects model was used if $I^2 < 25$ %, a random effects model was used if $I^2 > 25\%$. The left side of the forest plot indicates smoother movement, the right side indicates less smooth movement (measured in number of movement units/velocity peaks). Individuals with stroke demonstrate significantly less smooth movement (greater number of movement units) during reach-to-grasp in the central workspace only. SMD=standardised mean difference

Figure 6 A Movement smoothness central workspace

	Stroke			Control				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Fixed, 95% CI
*Michaelsen 2001 a	4.2	2	3	2.9	0.6	3	12.6%	0.70 [-1.03, 2.44]
*Michaelsen 2001 b	4.3	2.3	3	2.3	0.5	3	11.2%	0.96 [-0.89, 2.81]
Alt Murphy 2011 i	5.4	2.1	9	2.3	0.3	9	27.7%	1.97 [0.79, 3.14]
Alt Murphy 2011 j	11.1	3.6	10	2.3	0.3	10	18.5%	3.30 [1.86, 4.74]
Aprile 2014	4.56	2.36	6	1.13	0.35	6	18.0%	1.88 [0.42, 3.33]
Michaelsen 2001 c	4.3	1.9	3	2.6	0.4	3	11.0%	0.99 [-0.87, 2.85]
Michaelsen 2001 d	4.2	1.6	2	2.1	0.4	2	1.0%	1.03 [-5.11, 7.17]
Total (95% CI)			**36**			**36**	**100.0%**	**1.81 [1.19, 2.43]**

Heterogeneity: $Chi^2 = 7.36$, df = 6 (P = 0.29); $I^2 = 18\%$
Test for overall effect: Z = 5.73 (P < 0.00001)

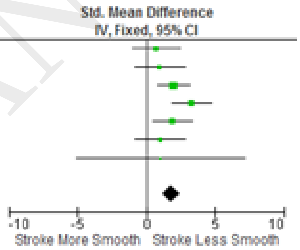

Figure 6 B Movement smoothness ipsilateral workspace

	Stroke			Control				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Chang 2008	2.48	0.86	17	1.65	0.29	17	50.1%	1.26 [0.52, 2.01]
Wu 2000	2.63	1.67	14	0.95	57	13	49.9%	0.04 [-0.71, 0.80]
Total (95% CI)			**31**			**30**	**100.0%**	**0.65 [-0.54, 1.85]**

Heterogeneity: $Tau^2 = 0.60$; $Chi^2 = 5.10$, df = 1 (P = 0.02); $I^2 = 80\%$
Test for overall effect: Z = 1.07 (P = 0.28)

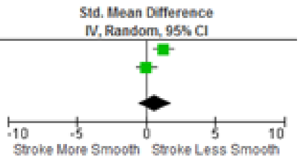

Figure 7 A, B - Forest Plots of the SMD of elbow range of motion during reach-to-grasp comparing individuals with stroke and control participants. A fixed effect model was used if $I^2 < 25\%$, a random effects model was used if $I^2 > 25\%$. The left side of the forest plot indicates a smaller range of motion, the right side of the plot indicates greater range of motion (measured in degrees). Individuals with stroke demonstrate significantly less elbow range of motion than adults when reaching in the central workspace. SMD=standardised mean difference, ROM= range of motion

Figure 7 Elbow Range of Motion all areas of the workspace

	Stroke			Control				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
*Levin 2002 e	79.8	14	3	77.9	13.3	3	8.3%	0.11 [-1.49, 1.72]
*Levin 2002 f	100	13.4	3	112	11.7	3	7.9%	-0.76 [-2.53, 1.00]
*Michaelsen 2001 a	4.2	2	3	28.6	9.4	3	4.5%	-2.87 [-6.07, 0.33]
*Michaelsen 2001 b	45.2	14.6	3	61.5	11.1	3	7.5%	-1.01 [-2.88, 0.87]
Alt Murphy 2011 i	60.5	10.4	9	53.5	7.8	9	10.2%	0.73 [-0.24, 1.69]
Alt Murphy 2011 j	67.2	11.9	10	53.5	7.8	10	10.1%	1.30 [0.32, 2.29]
Levin 2002 g	108.8	19.4	3	123.5	17.4	3	8.0%	-0.64 [-2.35, 1.08]
Levin 2002 h	115.6	17.5	2	131.9	15.4	2	3.6%	-0.57 [-4.32, 3.18]
Messier 2006	47	15.9	15	61	12.7	15	10.7%	-0.95 [-1.71, -0.19]
Michaelsen 2001 c	32.2	6.9	3	29.9	8.1	3	8.3%	0.24 [-1.37, 1.86]
Michaelsen 2001 d	59.1	11.2	2	69.9	6.5	2	3.0%	-0.67 [-4.96, 3.61]
Roby-Brami 2003A i	15.2	4	11	30.3	3.1	3	7.0%	-3.66 [-5.70, -1.61]
Roby-Brami 2003A j	6.7	2.1	4	30.3	3.1	4	2.0%	-7.75 [-13.26, -2.24]
Roby-Brami 2003B i	21.2	3.9	4	30.2	3.1	3	6.5%	-2.10 [-4.35, 0.14]
Roby-Brami 2003B j	9.6	1.7	4	30.2	3.1	4	2.3%	-7.17 [-12.28, -2.05]
Total (95% CI)			79			70	100.0%	-0.94 [-1.80, -0.08]

Heterogeneity: $Tau^2 = 1.66$; $Chi^2 = 48.16$, df = 14 ($P < 0.0001$); $I^2 = 71\%$
Test for overall effect: $Z = 2.13$ ($P = 0.03$)

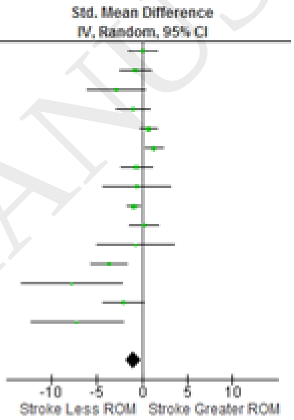

Table 1 Key to Forest Plots describes the reach-to-grasp task associated with the letter shown in the forest plot after the Author and Year. The key is applicable to the Forest Plots within the paper as well as the Supplemental Figures S1-S16**.**

Table 1 Key to Forest Plots

a. Trunk free target 1 (1/2 arm's length)

b. Trunk free target 2 (arm's length)

c. Trunk restrained target 1 (1/2 arm's length)

d. Trunk restrained target 2 (arm's length)

e. T1 1/2 arm's length

f. T2 arm's length

g. 1 1/3 arm's length

h. 2x arm's length

i. Good motor function

j. Poor motor function

k. Small object

l. Large object

m. Distance of 8 cm

n. Distance of 13 cm

o. Distance of 18 cm

p. Control R hand, stroke L hemisphere

q. Control L hand, stroke R hemisphere

r. Unilateral palmar grasp

s. Unilateral 3-finger grasp

t. Spherical

u. Cylindrical

v. Dominant arm of control group

w. 3-finger grasp hold

x. 3-finger grasp lift

y. Palmar grasp hold

z. Palmar grasp lift

Table 2 Summary of included studies in which reach-to-grasp occurred in the central or ipsilateral workspace, type of reach-to-grasp task, and movement speed.

Table 2 Summary of Task Conditions

Task	**Task Conditions**					
	Object Location					
	Central Workspace			**Ipsilateral Workspace**		
	Self-selected Speed	**Fast Speed**	**Speed not reported**	**Self-selected Speed**	**Fast Speed**	**Speed not reported**
Reach to Grasp	(50, 51)			(13)		(7, 39)
Reach to grasp and lift	(55)			(31-33, 36, 44)	(33)	(37)
Reach to grasp and transport	(46-49, 52, 54, 56-58)		(53)	(11, 30, 34, 38, 40, 41, 44, 59)		(35, 42, 43, 45)

Table 2 Summary of included studies in which reach-to-grasp occurred in the central or ipsilateral workspace, type of reach-to-grasp task, and movement speed.

Table 3 The potential risk of bias of included studies assessed using the modified Down’s and Black Tool (Online supplemental Table S2).

Table 3 Potential Risk of Bias of Included Studies

Study	Clear Hypothesis	Outcomes Described	Participant Characteristicts	Reproducible Reaching Task	Clear Findings	Estimates of Variability	Adervse Events	Attrition Described	Sample Representative	Blind Assessors	Consistent Protocol	Consistent Task	Robust Outcomes	Appropriate Statistical Tests
Alt Murphy														
Aprile														
Aruin														
Chang														
DeJong A														
DeJong B														
Kilbreath														
Lang														

Levin															
Lum															
Messier															
Michaelsen (04)															
Michaelsen (01)															
Nowak															
Patterson															
Raghavan															
Roby-Brami (03A)															
Roby-Brami (03B)															
Roby-Brami (97)															
Sangole															
Schaefer															
Van Dokkum															
Van Kordelaar															
Van Vliet (07)															
Van Vliet (09)															
Viau															
Wenzelburger															
Wu (00)															
Wu (09)															

Low Risk | Unclear Risk | High Risk

Table 4 Summary of the meta-analysis: SMD and 95% CI, number of participants included in the meta-analysis, outcome of meta-analysis of kinematic characteristics comparing individuals with stroke and control participants reaching in the central and ipsilateral workspace. A fixed effect model was used if $I^2 < 25\%$, and a random effects model was used if $I^2 > 25\ \%$. The fourth column describes the outcome of the meta-analysis of kinematic characteristics comparing individuals with stroke to control participants. Two meta-analyses demonstrated non-significant findings, reach path ratio in the central workspace, and smoothness of movement in the ipsilateral workspace. All other analyses demonstrated significant findings. SMD=standardized mean difference

Table 4 Summary of Meta-Analyses

Kinematic Characteristic Examined	**Number of Participants**	**SMD [95% CI]**	**Individuals with Stroke Compared to Control Participants**
Peak Velocity Central Workspace (all participants)	Stroke=106 Control=75	-1.48 [-1.94, -1.02]	↓
Peak Velocity Ipsilateral Workspace	Stroke=143 Control=80	-1.41 [-1.75, -1.08]	↓
Movement Time Central Workspace	Stroke=84 Control=53	1.97 [1.23, 2.72]	↑
Movement time Ipsilateral	Stroke=258	1.62 [1.20,	↑

workspace	Control=179	2.03]	
Reach Path Ratio Central Workspace (all participants)	Stroke=22 Control=22	0.57 [-0.09, 1.23]	=
Reach Path Ratio Ipsilateral Workspace	Stroke=110 Control=64	1.79 [1.06, 2.52]	↑
Trunk Contribution Central Workspace	Stroke=72 Control=51	1.55 [0.85, 2.25]	↑
Trunk Contribution Ipsilateral Workspace	Stroke=37 Control=16	1.58 [0.88, 2.27]	↑
Smoothness of Movement Central Workspace	Stroke=36 Control=36	1.81 [1.19, 2.43]	↓
Smoothness of Movement Ipsilateral Workspace	Stroke=31 Control=30	0.65 [-0.54, 1.85]	=
Elbow Range of Motion	Stroke=79 Control=70	-0.94 [-1.80, -0.08]	↓

Table 5 Summary of Sensitivity Analyses: SMD and 95% CI of the sensitivity analyses completed based on potentially overlapping participants, upper limb motor function (mild motor deficits and moderate-severe motor deficits), time since stroke, and non-age-matched control participants. The table describes the number of participants included in the meta-analsis, outcome of meta-analysis comparing individuals with stroke to healthy control participants during reach-to-grasp. The fourth column describes the outcome of the sensitivity analysis of kinematic characteristics comparing individuals with stroke to control participants. A fixed effect model was used if $I^2 < 25\%$, and a random effects model was used if $I^2 > 25$ %. Two sensitivity analyses demonstrated non-significant findings elbow extension excluding individuals with mild motor deficits and elbow extension excluding studies without age-matched controls. All other sensitivity analyses demonstrated significant findings.

Table 5 Summary of Sensitivity Analyses

Sensitivity Analysis	**Number of Participants**	**SMD [95% CI]**	**Individuals with Stroke Compared to Control Participants**
Excluding potentially overlapping participants			
Peak Velocity Central Workspace	Stroke: n=94 Control: n=63	-1.71 [-2.27, -1.16]	↓
Reach Path Ratio central workspace	Stroke: n=10 Control: n=10	0.55 [-0.51, 1.60]	**=**
Excluding individuals with stroke with mild motor deficits			
Peak Velocity Central Workspace	Stroke: n=86 Control: n=62	-1.38 [-1.78, -0.98]	↓

Movement Time Central Workspace	Stroke: n=64 Control: n=40	1.95 [0.96, 2.94]	↑
Trunk Contribution Central Workspace	Stroke: n=48 Control: n=36	1.42 [0.49, 2.35]	↑
Movement Smoothness Central Workspace	Stroke: n=27 Control: m=27	1.67 [0.76, 2.58]	↓
Elbow Extension (all areas of workspace)	Stroke: n=55 Control: n=55	-0.76 [-1.69, 0.17]	=
Excluding individuals after stroke with moderate motor deficits			
Peak Velocity Central Workspace	Stroke: n=92 Control: n=62	-1.37 [-1.87, -0.88]	↓
Movement Time Central Workspace	Stroke: n=70 Control: n=40	1.64 [0.96, 2.23]	↑
Trunk Contribution Central Workspace	Stroke: n=54 Control: n=33	1.28 [0.76, 1.80]	↑
Smoothness of Movement Central Workspace	Stroke: n=26 Control: n=26	1.47 [0.79, 2.16]	↓
Elbow Range of Motion (all areas of workspace)	Stroke: n=61 Control: n=52	-0.79 [-1.51, -0.07]	↓
Excluding participants less than three months after stroke			
Peak Velocity Ipsilateral Workspace	Stroke: n=104 Control: n=70	-1.40 [-1.77, -1.03]	↓
Movement Time Ipsilateral Workspace	Stroke: n=252 Control: n=173	1.69 [1.28, 2.09]	↑
Reach Path Ratio Ipsilateral workspace	Stroke: n=71 Control: n=54	1.95 [1.15, 2.76]	↑
Excluding studies with non-aged-matched controls (younger controls)			

Peak Velocity Central Workspace	Stroke: n=91 Control: n=68	-1.36 [-1.74, -0.99]	↓
Peak Velocity Ipsilateral Workspace	Stroke: n=125 Control: n=71	-1.33 [-1.69, -0.98]	↓
Movement Time Central Workspace	Stroke: n=69 Control: n=46	1.82 [1.01, 2.63]	↑
Movement Time Ipsilateral Workspace	Stroke: n=177 Control n= 142	1.75 [1.22, 2.27]	↑
Reach Path Ratio Ipsilateral Workspace	Stroke: n=87 Control: n=47	2.09 [1.06, 3.12]	↑
Trunk Contribution Central Workspace	Stroke: n=49 Control: n=37	1.23 [0.73, 1.72]	↑
Elbow Range of Motion (all areas of the workspace)	Stroke: n=56 Control: n=56	-0.17 [-0.85, 0.51)	**=**