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A systematic review of mechanisms of gait speed change post-stroke. Part 1: Spatiotemporal parameters and asymmetry ratios

Elizabeth C. Wonsetler, PT, DPT¹ and Mark G. Bowden, PhD, PT^{1,2,3}

¹Department of Health Sciences and Research, Medical University of South Carolina, Charleston, SC, USA

²Ralph H. Johnson VA Medical Center, Charleston, SC, USA

³Division of Physical Therapy, Medical University of South Carolina, Charleston, SC, USA

Abstract

Background—In walking rehabilitation trials, self-selected walking speed has emerged as the dominant outcome measure to assess walking ability. However, this measure cannot differentiate between recovery of impaired movement and compensation strategies. Spatiotemporal variables and asymmetry ratios are frequently used to quantify gait deviations and are hypothesized markers of recovery.

Objectives—The purpose of this review is to investigate spatiotemporal variables and asymmetry ratios as mechanistic recovery measures in physical therapy intervention studies post-stroke.

Methods—A systematic literature search was performed to identify physical therapy intervention studies with a statistically significant change in self-selected walking speed post intervention and concurrently collected spatiotemporal variables. Methodological quality was assessed using the Cochrane Collaboration's tool. Walking speed, spatiotemporal, and intervention data were extracted.

Results—46 studies met the inclusion criteria, 41 of which reported raw spatiotemporal measures and 19 reported asymmetry ratio calculations. Study interventions included: aerobic training (n=2), functional electrical stimulation (n=5), hippotherapy (n=2), motor dual task training (n=2), multidimensional rehabilitation (n=4), robotics (n=4), sensory stimulation training (n=8), strength/resistance training (n=4), task specific locomotor rehabilitation (n=9), and visually guided training (n=6).

Conclusions—Spatiotemporal variables help describe gait deviations, but scale to speed, so consequently, may not be an independent factor in describing functional recovery and gains.

Corresponding author: Elizabeth C. Wonsetler, PT, DPT (), Doctoral Student, Health and Rehabilitation Science, Graduate Assistant, Department of Health Sciences and Research, Medical University of South Carolina, Charleston, SC, College of Health Professions, 77 President Street, MSC 700, Charleston, SC 29425-7000, Office: 843-792-3477, Fax: 843-792-1358, wonsetle@musc.edu.

Mark G. Bowden, PhD, PT
Research Health Scientist, Research Service, Rehabilitation Research and Development, Department of Veterans Affairs Medical Center, Charleston, SC

Associate Professor, Department of Health Science and Research, Medical University of South Carolina, Charleston, SC
77 President Street, MSC 700 Charleston, SC 29425-7000, Office: 843-792-5036, Fax: 843-792-1358, bowdenm@musc.edu

Therefore, these variables are limited in explaining mechanistic changes involved in improving gait speed. Use of asymmetry measures provides additional information regarding the coordinative requirements for gait and can potentially indicate recovery. Additional laboratory-based mechanistic measures may be required to truly understand how walking speed improves.

Keywords

stroke; walking speed; rehabilitation; spatio-temporal analysis

Introduction

Stroke is the leading cause of disability in the United States, and the majority of those who survive stroke and achieve independent ambulation will demonstrate limitations in walking ability.^{1,2} Regaining the ability to ambulate and maximizing independence are two main goals of stroke rehabilitation, and these may be accomplished by compensating for remedial deficits, by promoting recovery of impaired movements, or by a combination thereof.³ Walking rehabilitation post-stroke has been historically dominated by strategies designed to compensate for impaired motor control, balance, and stabilization. However, improved understanding of neuroplasticity as a foundation for rehabilitation has led to a paradigm shift in which therapeutic interventions now target the nervous system's ability to recover normalized movement patterns.⁴ While "recovery" is often used to describe functional gains, it will be operationally defined within this manuscript as a return to pre-morbid patterns of movement associated with independent walking.⁵ Traditional outcome measurements, such as walking speed, are focused on performance of functional tasks, but these measures do not identify the mechanisms by which an individual recovers.

Self-selected walking speed (SSWS) is the most commonly used outcome measure of walking ability in locomotor rehabilitation,⁶ likely because it is simple,⁷ cost effective, reliable,⁸ valid,^{9,10} sensitive,¹¹ and specific.¹² Gait speed has been described as the sixth vital sign¹³ and has been shown to be a predictor of independence, functional level at home and within the community,¹⁴ hospital length of stay, discharge disposition,^{15,16} mortality,¹⁷ health status,¹⁸ and quality of life.¹⁹ However, simply because a patient post-stroke has learned to walk at an increased speed, this does not necessarily indicate that the patient walks without impairments or that they have recovered normalized and/or premorbid movements. Even with a normal walking speed, significant deficits in the gait pattern may occur.²⁰ These deficits potentially decrease patient safety and increase energy expenditure,²¹ leading to increased falls risk,²² increased walking-related fatigue,²³ and reduced ambulatory efficiency.²⁴ Regaining a normal, functional walking speed cannot distinguish between motor compensation (with an abnormal gait pattern) and motor recovery (with a normal gait pattern). While many interventions can lead to an increased walking speed, it is not clear which interventions promote acquisition and reinforcement of compensatory walking skills and/or which interventions promote recovery via changes in underlying mechanisms.

While SSWS has emerged as the dominant outcome measure for walking rehabilitation clinical trials, there remains inconsistent measurement of the mechanisms that may

contribute to recovery. Spatiotemporal variables, including cadence, step length/width parameters, and support time parameters, are frequently used to quantify gait deviations,^{21,25} calculate asymmetries,^{26,27} determine appropriate therapy,^{9,28} and track patient progress.^{29–31} Since these variables reflect alterations in movement patterns and degrees of impairment, using spatiotemporal asymmetry ratio measures may be effective as markers of recovery.³² Many therapy trials collect data that allude to recovery potential, but 1) there is no systematic and consistent use of outcome measures to determine the contributing mechanisms of speed change; and 2) there is no systematic pooling and assimilation of data to infer collective knowledge about mechanisms.

The purposes of this systematic review are to: 1) examine changes in spatiotemporal variables and asymmetry measures in intervention studies associated with significant changes in SSWS; and 2) differentiate between spatiotemporal raw variables and measures of asymmetry in their potential relationship with motor recovery.

Methods

Identification and selection of studies

Literature searches were performed in three databases: PubMed, Ovid, and CINAHL, on January 10, 2016. Search terms in PubMed and Ovid included the following medical subject headings: “Stroke” OR “Stroke, Lacunar” OR “Brain Infarction” OR “Cerebral Infarction” OR “Subarachnoid Hemorrhage” OR “Intracranial Hemorrhages” OR “Intracranial Aneurysm” AND “Gait” OR “Walking”. In CINAHL, identical search terms were used as CINAHL headings, except when unavailable. Consequently, key word searching was used for the terms “Brain Infarction” and “Cerebral Infarction”, and the medical subject heading “Intracranial Aneurysm” was substituted with the equivalent CINAHL heading “Cerebral Aneurysm”. Search filters consisted of English language and human subjects.

One reviewer (ECW) screened all titles and abstracts to identify relevant studies and delete duplicates. A second reviewer (MGB) screened 10% of the titles and abstracts for reliability. Full-text articles were then retrieved and assessed for eligibility by both reviewers. Studies selected for inclusion in the systematic review met the following inclusion criteria: (a) Adult participants, defined as >18 years of age; (b) All study participants are clinically diagnosed with stroke, regardless of time since diagnosis and lesion site; (c) Studies utilized any clinical physical therapy intervention to effect gait; (d) Studies included both a functional outcome measure of self-selected gait speed and a mechanistic outcome measure of spatiotemporal gait analysis; (e) Intervention group and/or comparison group yielded a statistically significant change in SSWS pre- to post-intervention.

Data extraction and analysis

One reviewer (ECW) extracted significant data elements from the included studies, and a second reviewer (MGB) verified the information. Extracted data included: sample demographics, design characteristics, intervention type and details, functional and mechanistic outcomes measured and method of measurement, gait speed data pre- and post-intervention, and statistically significant differences observed.

Effect sizes for change in gait speed were calculated, using Cohen's *d* (mean difference/SD), for all intervention and control groups in order to standardize the difference between means and increase ease of comparison between studies. Cohen's *d* effect size is interpreted as small (0.2), medium (0.5), or large (0.8).³³ In addition, each study was evaluated for changes in spatiotemporal variables, and when applicable, changes in spatiotemporal asymmetry ratios.

Assessment of study quality

Levels of evidence were applied using a Hierarchy of Evidence diagram adapted from Melnyk and Fineout-Overholt³⁴ accessed on the Medical University of South Carolina's Library website.³⁵ The methodological quality and bias was assessed using the Cochrane Collaboration's tool for assessing risk of bias.³⁶ The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement was used throughout this review.³⁷

Results

Flow of studies through the review

The outline of the search for relevant studies is shown in Figure 1. The initial search yielded 3,530 articles. After removing duplicates, screening records' titles and abstracts, and reviewing reference lists, 232 full text articles were retrieved. 186 articles failed to meet the inclusion criteria, so 46 studies were included for qualitative synthesis. Reviewers' agreement rate was 93.2%. Disagreements were resolved through discussion.

Description of studies

Of the included studies, one was published in the 1990's, eight in the 2000's, and 37 between 2010 and January 10, 2016 (Figure 2). One study design was classified as a case series, 11 as quasi-experimental, and 34 as randomized-controlled trials. The quality of the studies, including design, level of evidence, and assessment of risk of bias, is presented in Table 1.

Participant characteristics

Number of participants included in each study ranged from 8 to 61. All studies were conducted on chronic stroke survivors, except three that were done with early post-acute stroke patients.^{38–40} Also, one study examined and compared both the sub-acute and chronic populations.⁴¹ Participant demographics are presented in Table 2.

Functional gait outcome – gait speed

All included studies utilized gait speed as an outcome measure and showed a statistically significant increase in SSWS post-intervention. Gait speed was measured by utilizing an instrumented walkway,^{29–31,38,41–69} a motion analysis or instrumented gait analysis system,^{70–74} or by timing ambulation along the following distances: 9 meters;⁷⁵ 10 meters;^{39,40,76–78} or 30 meters.⁷⁹

Interventions that elicited functional improvements

The physical therapy interventions used within the included studies are variable. In order to structure the large number and variety of interventions, each study is assigned to one of 10 categories.

Aerobic training—Two included studies utilized an aerobic training intervention. Aerobic treadmill⁵⁹ training produced an effect size of 0.34, while aerobic over-ground, reciprocal stepping training⁴¹ had effect sizes of 0.88 and 1.22 for change in gait speed.

Functional electrical stimulation—Five included studies utilized interventions involving functional electrical stimulation in combination with cycling,⁴² body weight supported treadmill training (BWSTT),⁵⁴ mirror therapy,⁷⁰ conventional therapy,⁷⁷ or electrical stimulation with active ankle dorsi-flexion on a rocker board.⁴⁵ Change in gait speed effect sizes range dramatically from 0.26 to 3.54.

Hippotherapy—Two included studies involved hippotherapy, or horse-back riding therapy, interventions. The study utilizing hippotherapy⁵³ elicited an effect size of 3.25, and another involving a hippotherapy simulation⁴⁹ elicited effect size of 0.67.

Motor dual task training—Of the included studies, two investigated the effects of dual task training/exercise.^{58,62} The change in gait speed effect sizes range from 0.31 to 1.50.

Multidimensional rehabilitation—Four of the included studies have multidimensional exercise programs that included strengthening and aerobic exercise,⁶⁰ circuit class training,⁴⁰ circuit tilt table,⁶⁶ or hydro-kinesiotherapy.⁴⁷ Change in gait speed effect sizes range from 0.41 to 2.13.

Robotics—Of the included studies, four involved robotic interventions, specifically: robotic gait training with body weight support,^{48,61} or ankle training with a robotic device.^{38,46} The change in gait speed effect sizes that resulted range from 0.32 to 6.03.

Sensory stimulation training—Eight of the included studies investigated interventions involving sensory stimulation training, including rhythmic auditory stimulation,⁶⁴ spinal stabilization with visual feedback,⁴³ auditory stimulation training,⁵¹ exercise with TENS,⁶⁸ ankle proprioceptive control training,³⁰ local vibration stimulus training program,⁵⁶ segmental muscle vibration,⁷⁴ and biofeedback.⁶³ Change in gait speed effect sizes following sensory stimulation training range from 0.06 to 2.80.

Strength/Resistance training—Four of the included studies utilized a strength training intervention through progressive resistance training,⁵⁵ power training,⁶⁷ exercise standing on one leg,³¹ or by comparing eccentric to concentric resistance training.⁷⁹ The change in gait speed effect sizes range from 0.40 to 2.43.

Task specific locomotor rehabilitation—Nine of the included studies investigated the effects of locomotor training and variations thereof. Study interventions included: BWSTT,^{73,78,80} treadmill training without body weight support,³⁹ body weight support over ground

walking,⁷¹ turning-based treadmill training,⁴⁴ backward walking training,⁷⁵ walking exercise on a ramp,⁵⁷ and gait training with a cane.⁶⁵ Change in gait speed effect sizes that resulted range from 0.25 to 3.00.

Visually-guided training—Six of the included studies investigated the effects of visually guided interventions such as action observation training,⁵⁰ motor imagery,²⁹ mirror therapy,⁷² or virtual or augmented reality interventions.^{52,69,76} The resulting effect sizes range from 0.20 to 1.16.

Potential mechanisms of change - spatiotemporal parameters and asymmetry ratios

Spatiotemporal variables are variables concerning placement of the feet and time aspects of events during the gait cycle, and include step length, stride length, cadence, single limb support time, double limb support time, stance time, and swing time measurements. The 46 included studies analyzed gait using a variety of spatiotemporal variables and/or asymmetry ratio calculations, recorded for either or both the paretic and non-paretic limbs. Refer to Table 2 for details regarding inclusion of spatiotemporal parameters and asymmetry ratios and significant changes observed post-intervention. Statistically significant improvements reported were observed in the hypothesized direction of change based on each variable (i.e. cadence and step length increased, while double limb support decreased). The most commonly used data collection method for spatiotemporal variables is through the use of an instrumented walkway or motion analysis system. All included studies utilized these methods expect two: one study used inked footprints on paper for quantitative gait analysis⁴⁰ and one used footswitches on the paretic side.⁷⁹

Step length—Of the included studies, 24 recorded paretic step length; of those, 23 found statistically significant changes in the paretic step length following the physical therapy intervention.^{29–31,38,39,43,50,52,54–59,67–73,76,77} Non-paretic step length was less commonly reported (n=11). Nine of those studies found statistically significant changes in non-paretic step length.^{29,30,38,39,52,58,59,67,73}

Stride length—28 studies recorded paretic stride length, and of those, 27 found statistically significant changes in this spatial measure following physical therapy intervention.^{29–31,46,49–52,54,55,58–60,62–64,66,68–77} Non-paretic stride length was less commonly reported (n=8). However, non-paretic stride length was found to be statistically significant in all eight of those studies.^{30,49,51,52,58,64,71,74}

Cadence—Cadence was the most commonly reported of all the spatial and temporal parameters, as 30 studies included this measure. Of those 30 studies, cadence was found to significantly increase in 25 of them.^{29,30,39,40,43,46,47,49,50,52,54,56,58–60,62,64,66–70,75–77}

Single limb support—Paretic single limb support was reported in 13 studies and was found to be statistically significant in nine.^{29,41,46,50,51,56,58,65,72} Non-paretic single limb support was reported in 4 studies and found to be statistically significant in half of them.^{51,58}

Double limb support—Double limb support was reported, as a period of time or as a phase of gait cycle, in 11 of the included studies. Seven of those studies found a statistically

significant change in this variable.^{29,46,47,55,59,66,69} More specifically, paretic double limb support was reported and statistically significant in four other included studies.^{49,50,58,64} Additionally, three of those four studies reported non-paretic double limb support, all exhibiting statistically significant changes.^{49,58,64}

Stance time—Stance time/phase was reported in six studies and found to be statistically significant in only two of them.^{47,69} Three studies reported paretic stance time, two of which found statistically significant changes.^{31,59} Lastly, non-paretic stance time was reported in two studies and was not found to have a statistically significant change in either.

Swing time—Paretic limb swing time was reported in eight of the included studies, and it was found to be statistically significant in five of those.^{31,47,59,69,79} Non-paretic limb swing time was reported in only two studies^{59,73} and was not statistically significant in either.

Asymmetry ratios—Additionally, 19 studies quantified the spatiotemporal variables by calculating measures of asymmetry.^{29,38,40,41,43–45,48,51,53,59–62,66,73,75,78,80} These methods varied and are listed in Table 3.

Discussion

This systematic review sought to identify mechanistic variables that potentially detect motor recovery and explain improvements in gait speed following physical therapy interventions in the stroke population. Measuring mechanistic factors, such as spatiotemporal parameters and asymmetries, may assist in the understanding of how walking speed improves, and will enable researchers and therapists to better focus rehabilitation of gait post-stroke. Spatiotemporal parameters and asymmetry measures are commonly used outcomes, likely due to the decreased cost, increased ease, and time effectiveness of collecting this type of data. Although closely related, as raw spatiotemporal parameters are used to calculate asymmetry ratios, asymmetry improvements may reflect whole body gains in coordination and movement patterning, and likely provide differing insight into gait events and mechanisms.

Of the 41 studies that report raw spatiotemporal measures, 38 found at least one parameter to be significantly changed, indicating that these measures are highly responsive to physical therapy interventions, but may not differentiate the mechanisms by which individuals alter walking speed. Within the three studies where a spatiotemporal parameter was not significantly altered, the change in walking speed was minimal, with small to moderate effect sizes ranging from 0.33 to 0.61.^{42,44,48} While significantly improved from baseline, these increases were perhaps not large enough to generate concomitant changes in spatiotemporal factors. Also, within these three studies, they reported only one or two raw spatiotemporal variables each, and it is possible recovery may have been observed elsewhere. These studies investigated the interventions functional electrical stimulation,⁴² robotic gait training,⁴⁸ and turning-based treadmill training,⁴⁴ and the results imply that perhaps they were not robust enough to promote spatiotemporal improvements. There does not appear to be any commonality within the interventions that resulted in specific spatiotemporal changes, and thus, we cannot interpret the relationships between

spatiotemporal parameters and these varying interventions. The high number of significant spatiotemporal measurement changes observed may be due to the number of parameters, such as step length, stride length, and cadence that scale to gait speed.⁸¹ Consequently, these measures are not representative of factors that are independent of the changes in walking speed. Due to this dependent relationship, spatiotemporal measures may not give insight into the true mechanism of change. For example, do increases in walking speed drive increases in step/stride length or do step/stride length increases drive the speed change? In actuality, all are possibly a product of a separate mechanism, such as improved propulsive force production, that results from the intervention. Similarly, cadence and speed increases can both be a product of improved motor control, thus improved capacity to increase the frequency of the reciprocal gait pattern. One must apply restraint in considering these variables as the mechanism that drives recovery, as they may similarly be a product of that recovery.

Spatiotemporal asymmetry measures describe the body's ability to produce normalized walking patterns and evaluate interlimb coordination and, therefore, may represent the potential for a clinical measurement to indicate motor recovery. Asymmetry measures were calculated in 19 of the included studies, with only 10 studies yielding statistically significant changes following the intervention. All but two of those studies reported changes in raw spatiotemporal variables.^{44,48} Thus, it is probable that gait asymmetry ratios are more sensitive measures and better reflect recovery as compared to raw spatiotemporal measures. However, as with the raw spatiotemporal parameters, there does not appear to be any consistency within the interventions that did and did not elicit specific spatiotemporal asymmetry changes. Detecting a pattern regarding what therapies improve asymmetries became even more difficult due to the variability of the calculations (see Table 3) used within the included studies. Likewise, no conclusions were definitively drawn regarding asymmetry measures and their relationship to walking changes due to the calculation variability of ratio measurements. This lack of standardization of gait asymmetry measures in the stroke population has been addressed by Patterson et al. with recommendations made to use the symmetry ratio (paretic variable/non-paretic variable) for ease of interpretation.²⁷ Even so, the current data do not conclusively demonstrate that asymmetry measures reflect recovery, and one must continue to apply restraint in considering asymmetry measures to be the mechanism of change. Although there is potential here to assess recovery in the future, it would require a more standardized battery of assessments of true mechanisms, that reflect motor control and force production, to understand the improvements in interlimb asymmetry and coordination.

This review of the literature identifies the need for more direct measures to quantify the mechanisms by which human walking is recovered after stroke. While spatiotemporal parameters provide therapists with the ability to better track patient progress regarding gait deviations, these measures are intermediary, since they closely relate to walking speed. True mechanistic measures are required to provide a greater understanding of how physical therapy interventions improve gait speed. This will likely require more laboratory-based measures of motor recovery, including measures of exercise capacity, muscle activation, movement analysis, and force production that will all be examined in Part II of this review.

Limitations

There were a number of limitations to this systematic review. First, there was a high risk of bias within many of the included studies. This is primarily due to study design, level of evidence, lack of control group, and decreased use of randomization. Also, several experiments included small sample sizes. Another limitation is the high variability of the included studies due to the variation in type, duration, and intensity of the interventions used, as well as the methods in which spatiotemporal parameters were collected and spatiotemporal asymmetry ratios calculated. Additionally, the gait speeds reported in this systematic review were self-selected. Although SSWS appears to be more common, it has been suggested that assessment at one's self selected speed alone may not be sufficient to identify underlying impairments in hemiparetic walking.⁸² Furthermore, raw spatiotemporal variables are likely not sensitive in detecting true mechanistic changes, as they are a product of the functional changes following the intervention. Lastly, although it is likely that neurological recovery is greater in the early post-acute stroke population, because there were so few of the included studies examining patients during the sub-acute phase, no definitive assessment could be made regarding a differential level of recovery.

Clinical and research implications

This systematic review highlights specific physical therapy interventions that resulted in gait speed improvements with concurrent measurement of spatiotemporal variables. Spatiotemporal measurements are clinically feasible and provide more quantifiable gait information than gait speed alone. As the causal links are still missing with this method of gait measurement, researchers have begun to connect asymmetry ratios and measured patterns of ground reaction force development.²⁶ Due to these missing links, there is great potential and opportunity for researchers to link laboratory-based measurements to clinical improvements.^{28,83}

Conclusions

Our aim was to review the available literature in order to identify potential mechanisms associated with speed changes, as they relate to physical therapy interventions and outcomes after stroke. The methods in which gait is analyzed have evolved dramatically, and there has been a shift to not only understand, but also to quantify the underlying mechanistic changes that contribute to the functional gains. The growth of literature observed in this systematic review demonstrates the sharp increase in studies including both functional and mechanistic measures beginning in the late 2000s (Figure 2). The recent evolution of the gait literature and the increased ease of collecting spatiotemporal parameters in the clinic has led to an increase in spatiotemporal data, which helps to better describe gait deviations but may not be able to explain mechanistic changes. Spatiotemporal variables are often utilized as a surrogate for recovery, however, these variables may be a by-product of the speed at which someone walks and thus not independent in describing functional recovery and gains. The use of asymmetry measures may provide additional information regarding the coordinative requirements for gait and can potentially indicate recovery. Additional mechanistic measures may be required to gain a greater understanding of how walking speed improves. Part II of this review will examine more laboratory-based measures of motor recovery including

measures of exercise capacity, muscle activation, movement analysis, and force production and will similarly discuss them within the context of increased walking speed.

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Abbreviations

SSWS	self-selected walking speed
BWSTT	body weight supported treadmill training

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Figure 1.
Flow of studies through the review.

Figure 2.
Growth of the literature including both functional and mechanistic measures.

Quality of included studies

Table 1

Study, Year	Design/Level of evidence ³⁴	Assessing Risk of Bias ³⁶					Blinding	Incomplete data	Selective outcome reporting	Other sources of bias
		Sequence Generation	Allocation concealment	Blinding	Incomplete data	Selective outcome reporting				
Alon, 2011	Case Series/VI	No	No	No	Yes	No	No	Yes	No	No
Bowden, 2013	Quasi-experimental design/III	No	No	No	Yes	Yes	No	Yes	Yes	Yes
Cha, 2014	RCT/II	Unclear	Yes	Unclear	Yes	Yes	Unclear	Yes	Yes	Yes
Chae, 2011	RCT/II	Unclear	Unclear	Unclear	Yes	Yes	Unclear	Yes	Yes	No
Chen, 2014	RCT/II	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cheng, 2010	RCT/II	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Combs-Miller, 2014	RCT/II	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dunsky, 2008	Quasi-experimental design/III	No	No	No	Yes	Yes	No	Yes	No	Yes
Engardt, 1995	Quasi-experimental design/III	No	Unclear	Unclear	Yes	Yes	Unclear	Yes	Yes	Yes
Forrester, 2011	Quasi-experimental design/III	No	No	No	Yes	Yes	No	Yes	Yes	Yes
Forrester, 2014	RCT/II	Unclear	No	No	Yes	Yes	No	Yes	No	Yes
Fumari, 2014	RCT/II	Unclear	Unclear	Unclear	Yes	Yes	Yes	Yes	Yes	Yes
Gama, 2015	RCT/II	Unclear	Unclear	Unclear	Yes	Yes	Yes	Yes	Yes	No
Holleran, 2014	RCT/II	No	No	No	Yes	Yes	No	Yes	Yes	Yes
Hornby, 2008	RCT/II	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Ji, 2014	RCT/II	Unclear	Unclear	Unclear	Yes	Yes	Unclear	Yes	Yes	Yes
Ji, 2015	RCT/II	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Jonsdottir, 2010	RCT/II	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Jung, 2015	RCT/II	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Kim, 2009	RCT/II	Unclear	Unclear	Unclear	Yes	Yes	Yes	Yes	Yes	Yes
Kim, 2012	RCT/II	Yes	Unclear	Unclear	Yes	Yes	Unclear	Yes	Yes	Yes
Kim, 2013	RCT/II	Unclear	Yes	Unclear	Yes	Yes	Unclear	Yes	Yes	Yes
Kim, 2014	Quasi-experimental design/III	No	No	No	Yes	Yes	No	Yes	Yes	Yes
Kim, 2015	RCT/II	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Yes	Yes
Lee, C-W, 2014	Quasi-experimental design/III	Unclear	Unclear	Unclear	Yes	Yes	Unclear	Unclear	Yes	No

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Study, Year	Design/Level of evidence ³⁴	Assessing Risk of Bias ³⁶						Selective outcome reporting	Other sources of bias
		Sequence Generation	Allocation concealment	Blinding	Incomplete data				
Lee, C-H, 2014	RCT/II	Yes	Yes	Yes	Yes		Yes	Yes	Yes
Lee, H-J, 2013	RCT/II	Yes	Unclear	Yes	Yes		Yes	Yes	Yes
Lee, I-H, 2015	RCT/II	Unclear	Unclear	Yes	Yes		Yes	Yes	Yes
Lee, N-K, 2013	RCT/II	Unclear	Unclear	Unclear	Yes		Yes	Yes	Yes
Lee, S-W, 2013	RCT/II	Yes	Yes	Yes	Yes		Yes	Yes	Yes
Morgan, 2015	Quasi-experimental design/III	No	No	No	Yes		No	No	Yes
Paoloni, 2010	RCT/II	Yes	Yes	Yes	Yes		Yes	Yes	Yes
Park, 2013	Quasi-experimental design/III	No	No	No	Yes		Yes	Yes	Yes
Park, 2014	RCT/II	Yes	Unclear	Unclear	Yes		Yes	Yes	Yes
Patterson, 2008	Quasi-experimental design/III	No	No	No	Yes		Yes	Yes	Yes
Sabut, 2010	RCT/II	Unclear	Unclear	Yes	Yes		Yes	Yes	Yes
Seo, 2012	RCT/II	Unclear	Unclear	Unclear	Unclear		Yes	Yes	Yes
Shim, 2012	RCT/II	Yes	Unclear	Unclear	Yes		Yes	Yes	Yes
Sousa, 2011	Quasi-experimental design/III	No	No	No	Yes		Yes	Yes	Yes
Teixeira-Salmela, 2001	Quasi-experimental design/III	No	No	No	Yes		Yes	Yes	Yes
Verma, 2011	RCT/II	Yes	Yes	Yes	Yes		Yes	Yes	Yes
Westlake, 2009	RCT/II	Yes	Unclear	Unclear	Unclear		Yes	Yes	Yes
Yang, 2005	RCT/II	Yes	Yes	No	Yes		Yes	Yes	Yes
Yang, 2007	RCT/II	Yes	Yes	Yes	Unclear		Yes	Yes	Yes
Yom, 2015	RCT/II	Unclear	Unclear	Unclear	Yes		Yes	Yes	Yes
You, 2012	RCT/II	Unclear	Unclear	Unclear	Yes		Yes	Yes	Yes

RCT: Randomized Controlled Trial

Overview of participant characteristics, intervention categories, gait effect sizes, and spatiotemporal parameters

Table 2

Study, Year	Participant Demographics		Intervention		Outcome Measures	
	n	Age (yrs)	Time Since Stroke	Category	Grp	ES
Chronic Stroke						
Alon, 2011	10	59 ± 13.25	7.7 ± 10.56 (y)	FES	I	0.33
Bowden, 2013	27	58.74 ± 12.97	22.70 ± 16.38 (m)	TSLR	I	1.11
Cha, 2014	10	59.8 ± 11.7	14.5 ± 5.5 (m)	SST	I	1.18
	10	63.0 ± 14.1	14.7 ± 5.4 (m)		C	0.22
Chae, 2011	9	56.33	21.44 ± 6.85 (m)	SST	I	0.06
Chen, 2013	15	54.8 ± 8.1	2.2 ± 2.0 (y)	TSLR	I	0.61
Cheng, 2010	8	52.87 ± 8.74	33.6 ± 37.9 (m)	FES	I	0.71
Combs-Miller, 2014	10	65.50 ± 6.17	60.00 ± 51.68 (m)	TSLR	C	0.45
Dunsky, 2008	17	57.47 ± 9.25	45.94 ± 27.14 (m)	V-G T	I	0.88
Engardt, 1995	10	64.6 ± 6.2	27.8 ± 12.0 (m)	S/R T	Ib	0.40
Forrester, 2011	8	62.38 ± 10.45	72.5 ± 36.7 (m)	R	I	0.93
Fumari, 2014	20	68 ± 3	7 ± 1.6 (m)	M-DR	I	1.20
	20	72 ± 5	6 ± 1.4 (m)		C	0.50
Gama, 2015	14	52.92 ± 9.51	35.36 ± 26.87 (m)	TSLR	I	0.50
Hornby, 2008	24	57 ± 10	50 ± 51 (m)	R	I	0.37
	24	57 ± 11	73 ± 87 (m)		C	0.59
Ji, 2014	10	52.9 ± 9.9	7.1 ± 3.4 (m)	FES	Ia	3.54
	10	48.6 ± 8.5	7.3 ± 2.9 (m)		Ib	2.45
	10	54.6 ± 9.2	6.7 ± 2.3 (m)		C	1.28
Ji, 2015	16	55.2 ± 7.5	4.3 ± 1.5 (m)	V-G T	I	0.79

Study, Year	Participant Demographics			Intervention		Outcome Measures	
	n	Age (yrs)	Time Since Stroke	Category	Grp	ES	Spatiotemporal Parameters
	15	54.3 ± 8.7	4.5 ± 1.3 (m)		C	0.49	
Jonsdottir, 2010	10	61.6 ± 13.1	5.9 ± 10.5 (y)	SST	I	1.01	Stride Length (%h) *
Jung, 2015	11	56.4 ± 11.1	6.2 ± 2.5 (m)	TSLR	I	0.94	P Single Limb Support Phase (%) *
Kim, 2009	12	52.42 ± 10.09	25.91 ± 9.96 (m)	V-G T	I	0.75	Cadence (steps/min) *, Step time (s) *, Swing Time (s), Stance Time (s), Single Limb Support Time (s), Double Limb Support Time (s), Step length (cm) *, Stride length (cm) *
Kim, 2012	10	65.2 ± 6.8	15.8 ± 2.3 (m)	SST	I	2.80	P Stride Length (cm) *, NP Stride Length (cm) *, Stride Length Ratio *, P Single Limb Support Time (ms) *, NP Single Limb Support Time (ms) *, Single Support Time Ratio *
	10	64.5 ± 8.1	15.3 ± 3.0 (m)		C	1.75	
Kim, 2013	9	55.3 ± 12.1	8.3 ± 3.3 (m)	V-G T	Ia	1.16	Cadence (steps/min) *, P Step Length (cm) *, P Stride Length (cm) *, P Single Limb Support (%), P Double Limb Support (%) *
	9	54.8 ± 8.8	7.3 ± 0.7 (m)		Ib	0.57	
	9	59.8 ± 8.9	8.5 ± 3.6 (m)		C	0.45	
Kim, 2014	17	63.9 ± 8.7	23.6 ± 2.8 (m)	H	I	0.67	Cadence (steps/min) *, P Stride Length (cm) *, NP Stride Length (cm) *, P Double Limb Support (%), NP Double Limb Support (%) *
	10	59.20 ± 7.72	8.12 ± 4.95 (m)	M-DR	Ia	0.60	Cadence (step/min) *, P Stride Length (cm) *
Kim, 2015	10	58.53 ± 11.83	7.99 ± 3.85 (m)		Ib	0.68	Gait Symmetry Ratio *, Double Support Period (%) *
Lee, C-W, 2014	15	63.8 ± 6.2		H	I	3.25	Step Length Asymmetry Ratio (%) *
Lee, C-H, 2014	10	47.9 ± 12.0	11.7 ± 4.5 (m)	V-G T	I	0.95	Cadence (steps/min) *, P Step Length (cm) *, NP Step Length (cm) *, P Stride Length (cm) *, NP Stride Length (cm) *
	15	52.47 ± 9.41	4.0 ± 0.41 (m)	FES	I	2.00	Cadence (steps/min) *, P Step Length (cm) *, P Stride Length (cm) *
Lee, H-J, 2013	15	56.73 ± 7.24	4.07 ± 1.03 (m)		C	0.95	
Lee, N-K, 2013	14	60.3 ± 7.5	19.2 ± 5.2 (m)	S/R T	I	2.43	Step Length (cm) *, Stride Length (cm) *, Heel-to-heel Base of Support (%), Step Time (s) *, Double Support (%) *
	16	53.31 ± 8.37	56.94 ± 25.73 (m)	SST	I	0.58	Cadence (steps/min) *, P Step Length (cm) *, P Single Limb Support (s) *
Lee, S-W, 2013	15	55.73 ± 8.27	49.93 ± 29.97 (m)		C	0.16	
Morgan, 2015	12	56.0 ± 16.8	29.3 ± 19.7 (m)	S/R T	I	0.54	Cadence *, P Step Length *, NP Step Length *
	22	59.5 ± 13.3	1.85 ± 0.59 (y)	SST	I	0.69	Cadence (step/min), P Toe-off (%), NP Toe-off (%), P Step Length (m), NP Step Length (m), P Stride Length (m) *, NP Stride Length (m) *, P Step Width (m), NP Step Width (m), P Swing Velocity (m/s), NP Swing Velocity (m/s) *
Park, 2013	13	58.46 ± 8.53	53.15 ± 7.28 (m)	SST	I	0.75	Cadence (steps/min) *, P Step Length (cm) *, NP Step Length (cm) *, P Stride Length (cm) *, NP Stride Length (cm) *

Study, Year	Participant Demographics		Intervention		Outcome Measures	
	n	Age (yrs)	Time Since Stroke	Category	Grp	ES
Park, 2014	15	71.2 ± 3.46	18.66 ± 2.46 (m)	SST	I	0.47
Patterson, 2008	39	64 ± 8	20.55 ± 64 (m)	AT	I	0.34
	16	49.5 ± 8.9	20 (m)		I	0.46
Sabut, 2010	14	47.1 ± 12.4	15 (m)	FES	C	0.26
	20	61.5 ± 2.8	5.1 ± 4.8	TSLR	I	3.00
Seo, 2012	17	65.59 ± 5.81	16.29 ± 2.62 (m)		I	0.97
Shim, 2012	16	61.56 ± 6.17	17.44 ± 3.67 (m)	MDTT	C	0.31
	12	53.2 ± 7.5	4.6 ± 3.0 (y)	TSLR	I	0.57
Teixeira-Salmela, 2001	13	67.7 ± 9.2	7.7 ± 9.4 (y)	M-DR	I	0.41
Westlake, 2009	8	58.6 ± 16.9	43.8 ± 26.8 (m)	R	I	0.32
	13	63.38 ± 7.7	5.45 ± 3.03 (m)		I	1.29
Yang, 2005	12	63.42 ± 11.06	7.33 ± 2.42 (m)	TSLR	C	0.25
	13	59.46 ± 11.83	4.08 ± 3.13 (y)	MDTT	I	1.50
Yom, 2015	10	64.6	11.14 (m)		I	0.70
	10	78.1	11.63 (m)	V-G T	C	0.20
You, 2012	13	61.46 ± 5.12	13.30 ± 3.35 (m)		I	1.81
	14	59.07 ± 4.66	11.35 ± 2.84 (m)	S/R T	C	1.26
Chronic and Sub-Acute Stroke						
Holleran, 2014	10	55 ± 8.8	42 ± 58 (m)		Ia	0.88
	12	52 ± 13	3.2 ± 1.8 (m)	AT	Ib	1.22
Sub-Acute Stroke						
Forrester, 2014	18	63.3 ± 2.3	11.9 ± 1.5 (d)		I	6.03
	16	60.0 ± 3.1	10.8 ± 1.2 (d)	R	C	4.47

Study, Year	Participant Demographics		Intervention		Outcome Measures	
	n	Age (yrs)	Time Since Stroke	Category	Grp	ES
Lee, I-H, 2015	31	65.45 ± 4.37	40.93 ± 8.67 (d)	TSLR	Ia	2.00
	30	63.16 ± 8.22	34.77 ± 4.48 (d)		Ib	2.17
Verma, 2011	15	53.27 ± 8.53	6.07 ± 3.30 (w)	M-DR	I	2.13
	15	55.07 ± 6.80	6.60 ± 3.20 (w)		C	0.57

* denotes statistically significant change in mechanistic outcome measure
Mean ± SD

Time Since Stroke: d: days; w: weeks; m: months; y: years; Intervention Categories: AT: Aerobic Training; FES: Functional Electrical Stimulation; H: Hippotherapy; MDTT: Motor Dual Task Training; M-DR: Multi-dimensional Rehabilitation; R: Robotics; SST: Sensory Stimulation Training; S/R T: Strength/Resistance Training; TSLR: Task Specific Locomotor Rehabilitation; V-G T: Visually-Guided Training. Intervention Groups: I: Intervention; C: Control; Outcome Measures: ES: Effect Size; Spatiotemporal Parameters: P: Paretic; NP: Non-Paretic.

Table 3

Overview of spatiotemporal asymmetry ratio calculations

Spatial	Calculation	Study, Year
Step Length Asymmetry Ratios	$\frac{\text{paretic step length}}{\text{nonparetic step length}}$	Combs-Miller, 2014 ⁷⁸ Patterson, 2008 ⁵⁹ Forrester, 2014 ³⁸
	$1 - \frac{\text{paretic step length}}{\text{nonparetic step length}}$	* Cheng, 2010 ⁴⁵ Verma, 2011 ⁴⁰
	$\left 1 - \frac{\text{paretic step length}}{\text{nonparetic step length}} \right $	Chen, 2013 ⁴⁴ * Westlake, 2009 ⁶¹
	$100\% * \left(1 - \left 1 - \frac{\text{nonparetic step length}}{\text{paretic step length}} \right \right)$	* Holleran, 2014 ⁴¹
	$100 - \left 100 - 100 * \left(\frac{\text{nonparetic step length}}{\text{paretic step length}} \right) \right $	Hornby, 2008 ⁴⁸
Stride Length Asymmetry Ratio	$1 - \frac{\text{paretic stride length}}{\text{nonparetic stride length}}$	* Kim, 2012 ⁵¹ Verma, 2011 ⁴⁰
Paretic Step Ratio (aka Distance Phasing)	$\frac{\text{paretic step length}}{\text{stride length}}$	Bowden, 2013 ⁸⁰ Patterson, 2008 ⁵⁹
Temporal		
Single Support Time Asymmetry Ratios	$\frac{\text{paretic single support time}}{\text{nonparetic single support time}}$	* Dunskey, 2008 ²⁹
	$1 - \frac{\text{paretic single support time}}{\text{nonparetic single support time}}$	Cheng, 2010 ⁴⁵ * Kim, 2012 ⁵¹
	$\left 1 - \frac{\text{paretic single support time}}{\text{nonparetic single support time}} \right $	* Chen, 2013 ⁴⁴
	$2 * \left[\frac{(\text{paretic single limb support} - \text{nonparetic single limb support})}{\text{paretic single limb support} + \text{nonparetic single limb support}} \right] * 100$	* Yang, 2005 ⁷⁵
	$\frac{\text{nonparetic single support time (\% of gait cycle)}}{\text{paretic single support time (\% of gait cycle)}}$	Yang, 2007 ⁶²
Stance Time Symmetry Ratio	$\frac{\text{paretic stance time}}{\text{nonparetic stance time}}$	Combs-Miller, 2014 ⁷⁸ Patterson, 2008 ⁵⁹
	$\frac{\text{paretic stance (\% of gait cycle)}}{\text{nonparetic stance (\% of gait cycle)}}$	Patterson, 2008 ⁵⁹
Swing Symmetry Ratio	$\frac{\text{paretic swing time}}{\text{nonparetic swing time}}$	* Combs-Miller, 2014 ⁷⁸ Gama, 2014 ⁷³ Teixeira-Salmela, 2001 ⁶⁰
	$\frac{\text{paretic swing (\% of gait cycle)}}{\text{nonparetic swing (\% of gait cycle)}}$	Patterson, 2008 ⁵⁹
Step Time Symmetry Ratio	$\frac{\text{paretic step time}}{\text{nonparetic step time}}$	* Forrester, 2014 ³⁸

Spatial	Calculation	Study, Year
Gait Symmetry Ratio	$\frac{\left(\frac{\text{paretic swing time}}{\text{paretic stance time}} \right)}{\left(\frac{\text{nonparetic swing time}}{\text{nonparetic stance time}} \right)}$	* Kim, 2015 ⁶⁶

* denotes statistically significant change in mechanistic outcome measure

NOTE: Spatiotemporal asymmetry ratio equations not available for Chae, 2011 and Lee, 2014