Published in final edited form as:

Top Stroke Rehabil. 2017 July ; 24(5): 394–403. doi:10.1080/10749357.2017.1282413.

A systematic review of mechanisms of gait speed change post-stroke. Part 2: Exercise capacity, muscle activation, kinetics, and kinematics

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Abstract

Background—Regaining locomotor ability is a primary goal in stroke rehabilitation and is most commonly measured using changes in self-selected walking speed. However, walking speed cannot identify the mechanisms by which an individual recovers. Laboratory-based mechanistic measures such as exercise capacity, muscle activation, force production, and movement analysis variables may better explain neurologic recovery.

Objectives—The objectives of this systematic review are to examine changes in mechanistic gait outcomes and describe motor recovery as quantified by changes in laboratory-based mechanistic variables in rehabilitation trials.

Methods—Following a systematic literature search (in PubMed, Ovid, and CINAHL), we included rehabilitation trials with a statistically significant change in self-selected walking speed post-intervention that concurrently collected mechanistic variables. Methodological quality was assessed using the Cochrane Collaboration's tool. Walking speed changes, mechanistic variables, and intervention data were extracted.

Results—25 studies met the inclusion criteria and examined: cardiorespiratory function (n=5), muscle activation (n=5), force production (n=11), and movement analysis (n=10). Interventions included: aerobic training, functional electrical stimulation, multidimensional rehabilitation, robotics, sensory stimulation training, strength/resistance training, task-specific locomotor rehabilitation, and visually-guided training.

Conclusions—Following this review, no set of outcome measures to mechanistically explain changes observed in walking speed was identified. Nor is there a theoretical basis to drive the complicated selection of outcome measures, as many of these outcomes are not independent of

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walking speed. Since rehabilitation literature has yet to support a causal, mechanistic link for functional gains post stroke, a systematic, multi-modal approach to stroke rehabilitation will be necessary in doing so.

Keywords

stroke; walking speed; rehabilitation; recovery of function; exercise capacity; electromyography; kinetics; kinematics

Introduction

Of the 730,000 individuals who survive a stroke each year, 73% will have residual deficits in motor control and subsequent limitations in mobility,¹ making stroke the leading cause of disability in the United States. These limitations in mobility have a significant impact on locomotor ability, as even those who achieve independent ambulation will have significant deficits that persist in balance and gait speed.^{2,3} Regaining locomotor ability is one of the primary goals in stroke rehabilitation, and it is most commonly measured using changes in self-selected walking speed (SSWS).⁴ Not only is SSWS simple,⁵ cost effective, reliable,⁶ valid,^{7,8} sensitive,⁹ and specific,¹⁰ but it is also highly related to the severity of impairment and predicts functional walking status.¹¹⁻¹⁴ A paradigm shift has recently occurred in walking rehabilitation post-stroke to focus more on the nervous system's ability to recover normalized movement patterns instead of only teaching methods of compensation for impaired mobility, motor control, and balance.¹⁵ SSWS, however, does not identify the mechanisms by which an individual recovers when improving walking speed.

Little is known about the mechanisms (physiological or biomechanical) by which various physical therapy interventions may facilitate functional improvement of hemiparetic walking, as many studies of locomotor training only evaluate changes in functional outcomes (i.e. walking speed). While SSWS is the dominant outcome measure for walking rehabilitation clinical trials, there remains inconsistent measurement of the mechanisms that may be contributing to recovery. As demonstrated in Part I of this paper, spatiotemporal factors and measures of gait asymmetry are often associated with changes in gait speed to imply mechanistic contributions to functional recovery. However, most of these variables are directly associated with the speed at which someone walks and may not be an independent factor in describing functional recovery and gains. Collection of mechanistic variables beyond spatiotemporal variables (i.e. those which may independently represent physiologic and movement capacity changes which subserve changes in walking speed), could improve understanding of how walking speed was increased, if walking-specific recovery has occurred, and what impairment-based interventions may specifically improve walking function. This acquisition of knowledge may help drive the development of neurorehabilitation strategies, as well as provide a theoretical basis to drive outcome measurement choice.

Laboratory-based mechanistic variables, such as exercise capacity, muscle activation, force production, and movement analysis variables, reflect alterations in movement patterns and potential return to normalized gait, and thus may be better representatives of functional and

neurologic recovery than those clinically-based variables which are physiologically linked to walking speed. Since recent literature has begun to assess changes in these variables as intervention outcome measures in order to contribute to the emerging understanding of how improved walking speed is attained, a systematic approach or set of outcome measures to mechanistically explain the changes observed in SSWS may be detected via a literature review. Thus, the purposes of this systematic review are to: 1) investigate mechanistic gait outcomes following rehabilitation interventions, and 2) describe motor recovery as quantified by changes in exercise capacity, electromyography, kinematic, and kinetic variables as potential mechanistic contributors to significant changes in walking speed in individuals post-stroke.

Methods

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement was used throughout this review.¹⁶

Identification and selection of studies

On January 10, 2016, literature searches were completed in three databases: PubMed, Ovid, and CINAHL. All databases were searched from their date of inception to January 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 for that term. Thus, key word searching was used for the terms “Brain Infarction” and “Cerebral Infarction”, and the medical subject heading “Intracranial Aneurysm” was changed to the equivalent CINAHL heading “Cerebral Aneurysm”. Search filters consisted of published articles, English language, and human subjects.

One reviewer screened all titles and abstracts to identify relevant studies and delete duplicates. A second reviewer 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 criteria. 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 included any clinical physical therapy intervention to effect gait; (d) Studies included both a functional outcome measure of self-selected gait speed and a laboratory-based mechanistic outcome measure; (e) Studies yielded a statistically significant change in SSWS in the intervention group and/or comparison group pre- to post-intervention.

Data extraction and analysis

One reviewer extracted significant data elements from the included studies, and a second reviewer verified the information. Extracted data included: sample demographics, design characteristics, intervention type and details, functional and mechanistic outcomes measured, results, 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 (Table 2). Cohen's d effect size is interpreted as small (0.2), medium (0.5), or large (0.8).¹⁷

Assessment of study quality

Levels of evidence were applied using a Hierarchy of Evidence diagram adapted from Melnyk and Fineout-Overholt¹⁸ accessed on the Medical University of South Carolina's Library website.¹⁹ The methodological quality and bias was assessed using the Cochrane Collaboration's tool for assessing risk of bias.²⁰

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 and screening records' titles, abstracts and reference lists, 232 full text articles were retrieved. 207 articles failed to meet the inclusion criteria, so 25 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, nine in the 2000's, and 34 between 2010 and January 10, 2016 (Figure 2). One study design was classified as a case series, seven as quasi-experimental, and 17 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 63. Participant demographics are presented in Table 2.

Functional gait outcome – gait speed

All included studies showed a statistically significant increase in SSWS (also referred to as “comfortable walking speed” in the literature) post-intervention. Gait speed was measured by utilizing an instrumented walkway,²¹⁻²⁷ a motion analysis, or instrumented gait analysis, system,²⁸⁻³⁶ and/or by timing ambulation along the following distances: 6 meters;^{37,38} 10 meters;³⁹⁻⁴² 30 feet;^{27,43} 30 meters;⁴⁴ or 5, 10, and 30 meters.⁴⁵

Interventions that elicited functional improvements

The physical therapy interventions used within the included studies that were found to produce improvements in gait speed are variable. In order to structure the large number and variety of interventions, each study is assigned to one of 8 categories (Table 3).

Aerobic training—Two included studies utilized an aerobic treadmill training intervention.^{27,43} Change in gait speed effect sizes range from 0.34 to 1.83.

Functional electrical stimulation—Six included studies utilized interventions involving functional electrical stimulation (FES) in combination with cycling,²¹ fast locomotor treadmill training,^{37,38,41} or walking and conventional rehabilitation,⁴² or electrical stimulation with active ankle dorsiflexion on a rocker board.²³ The effect sizes range from 0.33 to 1.06.

Multidimensional rehabilitation—Two of the included studies have multidimensional exercise programs that included strengthening and aerobic exercise³⁶ (effect size = 0.41) and task-oriented physical therapy⁴⁵ (effect sizes could not be calculated from the graphical representation of the pre-post data).

Robotics—Two of the included studies involved robotic interventions, specifically the use of the Lokomat Gait Orthosis.^{28,32} Within one of those studies, it was actually the control group, which received therapist assisted locomotor training, that demonstrated a significant change in SSWS.³² The change in gait speed effect sizes that resulted range from 0.23 to 1.38.

Sensory stimulation training—Of the included studies, two investigated interventions involving sensory stimulation training, specifically electromyographic biofeedback²⁴ and segmental muscle vibration.³³ The intervention group's change in gait speed effect sizes were 1.01 and 0.69, respectively.

Strength/resistance training—Four of the included studies utilized a strength training intervention through power training,²⁶ by comparing eccentric and concentric resistance training,^{29,44} or strength training exercises.³⁴ The change in gait speed effect sizes range from 0.4 to 0.67.

Task specific locomotor rehabilitation—Six of the included studies investigated the effects of locomotor training and variations thereof. Study interventions included: Body weight support treadmill training (BWSTT),³⁹ BWSTT with incline,³¹ BWSTT and over ground walking,²² BWSTT with usual care,⁴⁰ body weight support (BWS) over ground walking,³⁵ and gait training with a cane.²⁵ Change in gait speed effect sizes that resulted range from 0.5 to 1.11.

Visually-guided training—One of the included studies investigated the effects of the visually guided intervention, motor imagery.³⁰ The change in gait speed effect size was 0.88.

Potential mechanisms of change

Cardiorespiratory function—Exercise testing, either on a cycle ergometer or treadmill, is used to determine aerobic capacity. It is often carried out prior to intervention to detect possible contraindications to exercise and to adapt exercise intensity if necessary. Post intervention, exercise testing is used to assess gains in aerobic capacity. Measurements taken

during or calculated following exercise testing include peak oxygen uptake (VO_{2peak}) and oxygen cost.

VO_{2peak} is the best measure of cardiorespiratory fitness used with patients that have functional impairments. A total of three of the included studies utilized sub-maximal or maximal exercise testing on either the treadmill with BWS⁴⁰ or treadmill without BWS^{27,43} to obtain VO_{2peak} . Of those studies, all three showed a statistically significant improvement in peak oxygen uptake post intervention.^{27,40,43}

Oxygen cost is the amount of oxygen consumed per kilogram body mass per unit distance (mL/kg/m). Two of the included studies calculated gait efficiency in this manner during a modified exercise test; one on the treadmill³⁸ and the other over ground⁴², both while utilizing FES. Significant improvements in oxygen cost were found in both studies. Walking economy, defined as oxygen consumed during submaximal effort normalized by speed (mL/kg/min), is a variation of cardiorespiratory functional measurement. It was obtained in a study by Macko et al.⁴³ during the treadmill exercise test. Significant improvements were found post intervention in this study.

Electromyography—Electromyography (EMG) is a technique used for detecting and recording the electrical activity produced by skeletal muscles. It can be used to determine the relationship of the neuromuscular activation signal to joint movements and to the gait cycle. Five of the included studies examined EMG activity either during isokinetic dynamometer strength testing,^{29,44} during gait,^{25,33} or while performing active dorsiflexion in sitting.⁴²

The two studies examining EMG during strength testing both observed the paretic and non-paretic quadriceps and hamstrings. Significant changes were found for agonist EMG activity, for slow eccentric and concentric actions.^{29,44}

Of the studies examining EMG during gait, Paoloni et al. studied the paretic and non-paretic tibialis anterior and medial gastrocnemius. Significant improvements were found in percentage of tibialis anterior activation during swing phase.³³ Whereas Jung et al. looked at the activation of the paretic and non-paretic gluteus medius and vastus medialis oblique, with percentage of non-paretic peak activity significantly improving for both muscles.²⁵

The study assessing active dorsiflexion in sitting addressed neuromuscular activation of the tibialis anterior and found significant improvements in EMG signal post intervention.⁴²

Kinetics—Kinetics describes mechanics of walking involving forces, work, energy, power, impulses, and moments. An advantage of kinetics is that the factor responsible for a motion can often be identified and quantified. Twelve of the included studies collected kinetic data.^{21,22,24,26,28,29,34,36,37,39,41,45}

Power: Eight of the included studies calculated and/or recorded muscular power during gait,^{24,28,34,36,45} while cycling,²¹ or with isokinetic dynamometer strength testing;^{26,29} Six of which found various statistically significant changes. Richards et al., Jonsdottir et al., and Brincks et al., all found significant improvements in peak paretic ankle plantar flexion power

during gait.^{24,28,45} Brincks et al. also found an increase in net peak concentric hip extension power during gait.²⁸ Alon et al. found a significant increase in bilateral lower extremity peak pedaling power.²¹ Clark et al. found significant changes in the rectus femoris, vastus medialis, semitendinosus, and biceps femoris post-intervention, as measured during strength testing.²⁹ Lastly, Morgan et al. found statistically significant gains in knee extensor peak power in the paretic and non-paretic lower extremities post intervention.²⁶

Ground reaction forces: Four studies collected data related to the paretic limb's capacity to generate propulsive (anterior ground reaction) force.^{22,37,39,41} Only one of those studies, conducted by Awad et al., found significant changes in the time integral of the propulsive forces from the paretic leg, peak paretic propulsive force, and propulsion symmetry post-intervention.³⁷

Moments: Only one of the included studies assessed joint moments during the gait cycle. Teixeira-Salmela et al. did not find any statistically significant change at the ankle, knee, or hip.³⁶

Work: Three studies calculated the work performed across the paretic and non-paretic ankle, knee, and hip joints during ambulation.^{34,36,39} Of these studies, only one found any significant changes: Parvataneni et al. detected significant increases in both paretic and non-paretic positive ankle plantar flexors, as well as non-paretic knee extensors.³⁴

Kinematics—Kinematics is the branch of mechanics dealing with the measurement of motion, without reference to the masses or forces involved.⁴⁶ It encompasses the measurements of individual joint angular rotations in addition to translations of segments and of whole body mass.⁴⁷ Ten of the included studies collected kinematic data; either via motion capture/analysis systems^{24,30-33,35-37,41} or with use of a footswitch and electrogoniometer.²³ Within all studies, joint motions of interest occurred in the sagittal plane, though in one study limb circumduction was also calculated, but no difference was found.³²

Seven studies measured ankle range of motion (ROM) at various times throughout the gait cycle,^{23,30-33,35,36} with only two finding significant improvements post-intervention. Paoloni et al. found significant changes in both the paretic and non-paretic ankle at heel strike, as well as improved paretic ankle plantar flexion and dorsiflexion during swing phase within the experimental group.³³ Sousa et al. found significant changes in minimum and maximum foot angles.³⁵

Of the eight studies examining the knee,^{24,30-33,35,36,41} only 25% (n=2) found significant changes in ROM throughout the gait cycle. Dunskey et al. and Sousa et al. found improvements in paretic knee ROM,^{30,35} with the latter study also showing improvements in non-paretic knee ROM.

Hip ROM data was collected in five studies,^{31-33,35,36} with only two finding a significant change. One of those studies found a significant change in paretic hip ROM throughout the gait cycle,³¹ and the other study found increased hip extension.³⁵

Only one study examined trunk angle,³⁵ but they did not find a significant change post intervention.

Lastly, two studies investigated the peak trailing limb angle, by calculating the peak of the planar angle between the laboratory's vertical axis and a vector joining the markers on the lateral malleolus and the greater trochanter.^{37,41} Of the two, Awad et al., found significant improvements in this variable post-intervention.³⁷

Discussion

This systematic review sought to identify the potential mechanisms of change that may explain improvements in gait speed and quantify motor recovery following physical therapy interventions in the stroke population. Improved understanding of the causal link of how a patient's walking speed improves may result from measuring mechanistic factors, such as exercise capacity, muscle activation, force production, and movement analysis variables. These factors are more laboratory-based, as opposed to clinically-based, and are not as commonly reported. Thus, little is known about the mechanisms (physiological or biomechanical) by which various physical therapy interventions may facilitate functional improvements in hemiparetic walking. By investigating the literature that reports both functional and mechanistic variables, a better understanding of the causal link of how walking speed improves may be identified.

This review of the literature establishes that there is no systematic approach or set of outcome measures to mechanistically explain the changes observed in SSWS. Within the various intervention categories (aerobic training, functional electrical stimulation, multidimensional rehabilitation, robotics, sensory stimulation, strength/resistance training, task specific locomotor rehabilitation, and visually guided training) and throughout the various outcomes measured, no single mechanistic variable or group of variables were identified. This may not only be indicative of the potential presence of numerous strategies utilized to achieve walking speed increases, but also demonstrates that gait speed is a complex functional activity and a multi-modal product of many processes. Gait speed has been upheld as sixth vital sign⁴⁸ due to its use as a general predictor of level of independence, functional capabilities at home and within the community,⁴⁹ hospital length of stay, discharge disposition from acute care,^{50,51} mortality,⁵² health status,⁵³ and quality of life.⁵⁴ It is similar to other vital signs in that it is not the only predictor of the aforementioned outcomes, it doesn't identify the underlying impairment causing the abnormality, nor does it identify how to treat the specific deficits. One must do subsequent testing to hopefully identify variables that contribute to or influence walking speed, but it can be challenging to detect the underlying physiological or biomechanical mechanisms without the appropriate outcome measurement methods.

Generally speaking, the field of rehabilitation is not yet to the point that underlying physiological and/or biomechanical mechanisms are readily identified to guide physical therapy treatment interventions. However, in this sample of intervention studies, many use mechanistic outcome measures that are theoretically linked to the intervention. Specifically, the studies applying aerobic training consistently used cardiorespiratory outcome measures;

the studies applying robotics measured motor control changes in force production and movement analysis variables; the studies applying strength/resistance training used EMG and kinetic outcomes; and lastly, the visually guided training intervention study monitored kinetic changes. On the contrary, several studies evaluated outcomes where it was difficult to determine how they theoretically linked mechanistically to the therapy interventions. For example, an intervention may be associated with changes in force production, but 1) force production may not have been the focus of the intervention; and 2) while force increased, it may not increase as much as it would have, had that been the theoretical focal point of the rehabilitation. Finally, some interventions are mechanistically multi-modal (i.e. task specific locomotor training and multi-dimensional rehabilitation), meaning that many different sub-systems contribute to functional change, thus, perhaps, it is appropriate that many apply a broad outcome measurement approach to assess the multiple potential mechanisms involved.

This review identified the need for a theoretical basis to drive the outcome measurement choice. This selection is further complicated, however, by the fact that some of these outcomes are not independent of walking speed. Those studies that collect mechanistic outcomes concurrently, or even those which examine the associations between speed change and mechanistic outcome measure change, are insufficient if we fail to recognize that these measures must change concurrently with changes in walking speed. This then begs the question, what is driving the change? Do the increases in force production and muscle activation drive increases in walking speed or does walking faster simply result in that much more force production and muscle activation? To address this question, we propose the idea of a systematic “toolbox” to collect mechanistic data in order to determine what the predictive factors are for gait speed changes depending on the type of interventions. This could be accomplished by either much larger trials, which is challenging and cost prohibitive, or a standardized set of outcomes in order to pool data into larger samples to allow for regressions and more complex predictive/causative models.

We recommend the following to address the needs identified as a result of this review: a multi-modal approach to stroke rehabilitation, reflecting the probable multi-modal mechanistic requirements to increase walking speed. We previously advocated this multi-modal approach to walking rehabilitation, recognizing that one of the limitations is the availability of quality outcome measures to guide treatment options.^{55,56} While there is not one therapy to fit all patients or address all deficits, if therapists can better identify and quantify the factors most limiting functional capacity and which of these factors may be improved with specific interventions, then the underlying mechanisms can be appropriately addressed to meet the goal of improved ambulation. Furthermore, increased understanding of underlying mechanisms can help distinguish between responders and non-responders to therapeutic interventions²² and may then guide the critical goal of selecting appropriate therapies to optimize the treatment of walking dysfunction after stroke.

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. 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 type of mechanistic variable collected. The interventions used may not have been high enough in intensity, long enough in duration, or specific enough to cause mechanistic changes. The mechanistic measures used may not have been sensitive to the changes that were observed, or perhaps it was all that was available to the investigators. Also, several experiments included small sample sizes. 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.⁵⁷ Lastly, although the mechanistic variables discussed in this review are likely sensitive in detecting mechanistic changes, they are costly, time consuming, and primarily performed in the laboratory setting, making it difficult for a therapist to collect this type of data in the clinic.

Conclusion

In conclusion, this systematic review has demonstrated that limited information is presented in the current literature on mechanistic changes that may contribute to recovery, thus there is minimal direct evidence that can be used as theoretical motivation for functional modifications. Such a theoretical framework for mechanisms underlying the adaptation of locomotor ability to training could potentially lead to a more comprehensive and integrative approach to the development of neurorehabilitation strategies for the clinical practice of post-stroke gait training. This review demonstrates that the rehabilitation literature, although growing in a promising direction, has not yet reached the point of identifying a causal, mechanistic link for functional gains post stroke, and that a systematic, multi-modal approach to stroke rehabilitation will be necessary in doing so.

Acknowledgments

This work was supported by a VA Career Development Award-2 RR&D N0787-W (MGB) and Institutional Development Award from the National Institute of General Medical Sciences of the NIH under grant number P20-GM109040 (MGB).

The contents do not represent the views of the Department of Veterans Affairs or the United States Government.

The authors would like to thank Heather Shaw Bonilha, PhD, CCC-SLP for her guidance in the early stages of this manuscript idea.

We certify that no party having a direct interest in the results of the research supporting this article has or will confer a benefit on us or on any organization with which we are associated and, if applicable, we certify that all financial and material support for this research and work are clearly identified in the title page of the manuscript.

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Abbreviations

SSWS self-selected walking speed

EMG	electromyography
ROM	range of motion
FES	functional electrical stimulation
BWSTT	body weight support treadmill training
VO_{2peak}	peak oxygen uptake
BWS	body weight support

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Figure 1.
Flow of studies through the review.

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

Table 1

Quality of included studies

		Assessing Risk of Bias ¹⁹							
	Design/Level of evidence ¹⁷	Sequence Generation	Allocation concealment	Blinding	Incomplete data	Selective outcome reporting	Other sources of bias		
Alon, 2011	Case Series/VI	No	No	No	Yes	No	No		
Awad, 2014	Quasi-experimental design/III	No	No	No	Yes	Yes	Yes		
Bowden, 2013	Quasi-experimental design/III	No	No	No	Yes	Yes	Yes		
Brincks, 2012	Quasi-experimental design/III	No	No	No	Yes	Yes	Yes		
Cheng, 2010	RCT/II	Yes	Yes	Yes	Yes	Yes	Yes		
Clark, 2013	Quasi-experimental design/III	No	Unclear	Yes	Yes	Yes	Yes		
Combs, 2012	Quasi-experimental design/III	No	No	Unclear	Yes	Yes	Yes		
Dunsky, 2008	Quasi-experimental design/III	No	No	No	Yes	No	Yes		
Engardt, 1995	Quasi-experimental design/III	No	Unclear	Unclear	Yes	Yes	Yes		
Gama, 2015	RCT/II	Unclear	Unclear	Yes	Yes	Yes	No		
Jonsdottir, 2010	RCT/II	Yes	Unclear	Yes	Yes	Yes	Yes		
Jung, 2015	RCT/II	Yes	Yes	Yes	Yes	Yes	Yes		
Lewek, 2009	RCT/II	Unclear	Yes	Unclear	Yes	Yes	Yes		
MacKay-Lyons, 2013	RCT/II	Yes	Yes	Yes	Yes	Yes	Yes		
Macko, 2005	RCT/II	Yes	Unclear	Yes	Unclear	Yes	Yes		
Morgan, 2015	Quasi-experimental design/III	No	No	No	Yes	No	Yes		
Paoloni, 2010	RCT/II	Yes	Yes	Yes	Yes	Yes	Yes		
Parvataneni, 2007	Quasi-experimental design/III	No	No	No	Yes	Yes	Yes		
Patterson, 2008	Quasi-experimental design/III	No	No	No	Yes	Yes	Yes		
Reisman (Changes), 2013	Quasi-experimental design/III	No	No	No	Yes	Yes	Yes		
Reisman (Time), 2013	Quasi-experimental design/III	No	No	No	Yes	Yes	Yes		
Richards, 2004	RCT/II	Yes	Unclear	Yes	Yes	Yes	Yes		
Sabut, 2010	Quasi-experimental design/III	No	No	No	Yes	Yes	Yes		
Sousa, 2011	Quasi-experimental design/III	No	No	No	Yes	Yes	Yes		
Teixeira-Salmela, 2001	Quasi-experimental design/III	No	No	No	Yes	Yes	Yes		

RCT: Randomized Controlled Trial

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Table 2
Overview of participant characteristics, intervention categories, gait effect sizes, and mechanistic outcome measures

Study, Year	Participant Demographics			Intervention		Outcome Measures	
	n	Age (y)	Time Since Stroke	Category	Grp	ES	Mechanistic Outcome
Alon, 2011	10	59 ± 13.25	7.7 ± 10.56 (y)	FES	I	0.33	Kinetics - Power *
Awad, 2014	13	61 ± 8.31	3.22 ± 3.05 (y)	FES	I	1.06	Kinematics * Kinetics - Propulsion *
Bowden, 2013	27	58.74 ± 12.97	22.70 ± 16.38 (m)	TSLR	I	1.11	Kinetics - Propulsion
Brineks, 2012	13	57.77 ± 9.08	36.77 ± 22.80 (d)	R	I	1.38	Kinetics - Power *
Cheng, 2010	8	52.87 ± 8.74	33.6 ± 37.9 (m)	FES	I	0.71	Kinematics
Clark, 2013	16	59.7 ± 10.9	12.8 ± 4.7 (m)	S/R T	Ia	0.48	EMG *
	18	63.2 ± 10.6	13.3 ± 4.9 (m)		Ib	0.67	Kinetics - Power *
Combs, 2012	15	59.9 ± 11.2	3.8 ± 3.2 (y)	TSLR	I	0.80	Kinetics - Propulsion, Work
Dunsky, 2008	17	57.47 ± 9.25	45.94 ± 27.14 (m)	V-G T	I	0.88	Kinematics *
Engardt, 1995	10	64.6 ± 6.2	27.8 ± 12.0 (m)	S/R T	Ia	0.40	EMG *
Gama, 2015	14	52.92 ± 9.51	35.36 ± 26.87 (m)	TSLR	I	0.50	Kinematics *
Jonsdottir, 2010	10	61.6 ± 13.1	5.9 ± 10.5 (y)	SST	I	1.01	Kinematics Kinetics - Power *
Jung, 2015	11	56.4 ± 11.1	6.2 ± 2.5 (m)	TSLR	I	0.94	EMG *
Lewek, 2009	9	53 ± 6	65 ± 68 (m)	R	C	0.23	Kinematics
MacKay-Lyons, 2013	24	61.5 ± 15.4	23.3 ± 5.7 (d)	TSLR	I	1.10	Exercise capacity *
	26	59.0 ± 12.7	23.1 ± 4.4 (d)		C	0.79	
Macko, 2005	32	63 ± 10	35 ± 29 (m)	AT	I	1.83	Exercise capacity *
	29	64 ± 8	39 ± 59 (m)		C	1.29	
Morgan, 2015	12	56.0 ± 16.8	29.3 ± 19.7 (m)	S/R T	I	0.54	Kinetics - Power *
Pholoni, 2010	22	59.5 ± 13.3	1.85 ± 0.59 (y)	SST	I	0.69	Kinematics * EMG *
Purvatani, 2007	28	64.2 ± 11.7	4.8 ± 7.0 (y)	S/R T	I	0.45	Kinetics - Power, Work *
Patterson, 2008	39	64 ± 8	20.55 ± 64 (m)	AT	I	0.34	Exercise capacity *

Study, Year	Participant Demographics			Intervention		Outcome Measures	
	n	Age (y)	Time Since Stroke	Category	Grp	ES	Mechanistic Outcome
Reisman (Ch...), 2013	11	61.8 ± 8	42 ± 35.4 (m)	FES	I	0.95	Exercise capacity *
Reisman (T...), 2013	13	61 ± 8.3	38.69 ± 36.63 (m)	FES	I	1.06	Kinematics Kinetics - Propulsion
Richards, 2004	32	62.9 ± 12	52.0 ± 22 (d)	M-DR	I		Kinetics - Power *
	31	60.7 ± 12	52.6 ± 18 (d)		C		
Sabut, 2010	15	51.4 ± 17.6	17.46 (m)	FES	I	0.82	Exercise capacity * EMG *
Sousa, 2011	12	53.2 ± 7.5	4.6 ± 3.0 (y)	TSLR	I	0.57	Kinematics *
Teixeira-Salmela, 2001	13	67.7 ± 9.2	7.7 ± 9.4 (y)	M-DR	I	0.41	Kinematics Kinetics - Power, Work, Moments

* denotes statistically significant change in mechanistic outcome measure

Mean ± SD

Time Since Stroke: d: days; 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; Mechanistic Outcome: EMG: Electromyography

NOTE: Raw gait speed data not available to calculate ES for Richards, 2004

Table 3
Overview of interventions and mechanistic outcome measures

Study, Year	Intervention			Outcome Measures
	Category	Grp	Type	Mechanistic Outcome
Macko, 2005	AT	I	Treadmill aerobic exercise training	Exercise capacity *
		C	Stretching and low intensity walking	
Patterson, 2008	AT	I	Treadmill aerobic exercise training	Exercise capacity *
Alon, 2011	FES	I	FES cycling	Kinetics - Power *
Awad, 2014	FES	I	FastFES locomotor training	Kinematics * Kinetics - Propulsion *
Cheng, 2010	FES	I	FES with ankle AROM	Kinematics
Reisman (Ch...), 2013	FES	I	FastFES locomotor training	Exercise capacity *
Reisman (T...), 2013	FES	I	FastFES locomotor training	Kinematics Kinetics - Propulsion
Sabut, 2010	FES	I	FES with conventional therapy	Exercise capacity * EMG *
Richards, 2004	M-DR	I	Specialized locomotor training	Kinetics - Power *
		C	Conventional therapy	
Teixeira-Salmela, 2001	M-DR	I	Aerobic exercise and strengthening	Kinematics Kinetics - Powers, Work, Moments
Brincks, 2012	R	I	Lokomat	Kinetics - Power *
Lewek, 2009	R	C	PT assisted locomotor training	Kinematics
Jonsdottir, 2010	SST	I	Electromyographic biofeedback	Kinematics Kinetics - Power *
Paoloni, 2010	SST	I	Segmental muscle vibration	Kinematics * EMG *
Clark, 2013	S/R T	Ia	Concentric resistance training	EMG *
		Ib	Eccentric resistance training	Kinetics - Power *
Engardt, 1995	S/R T	Ia	Concentric strength training	EMG *
Morgan, 2015	S/R T	I	Power training	Kinetics - Power *
Parvataneni, 2007	S/R T	I	Strength training	Kinetics - Power, Work *
Bowden, 2013	TSLR	I	Locomotor training	Kinetics - Propulsion
Combs, 2012	TSLR	I	BWSTT	Kinetics - Propulsion, Work
Gama, 2015	TSLR	I	BWSTT at 10% inclination	Kinematics *
Jung, 2015	TSLR	I	Gait training (with cane)	EMG
MacKay-Lyons, 2013	TSLR	I	BWSTT	Exercise capacity *
		C	Usual care	
Sousa, 2011	TSLR	I	BWS Overground Gait Training	Kinematics *
Dunsky, 2008	V-G T	I	Motor Imagery	Kinematics *

* denotes statistically significant change in mechanistic outcome measure

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; Intervention Type: FES: functional electrical stimulation; PT: physical therapist; BWSTT: body weight supported treadmill training; BWS: Body weight support; Outcome Measures: ES: Effect Size; Mechanistic Outcome: EMG: Electromyography

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