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Review

Effectiveness of rehabilitation interventions to improve paretic propulsion in individuals with stroke – A systematic review☆

J.F. Alingh[a,b,*], B.E. Groen[a,b], E.H.F. Van Asseldonk[c], A.C.H. Geurts[a,b], V. Weerdesteyn[a,b]

[a] Sint Maartenskliniek Research, Nijmegen, the Netherlands
[b] Department of Rehabilitation, Radboud University Medical Center, Nijmegen, the Netherlands
[c] Department of Biomechanical Engineering, University of Twente, Enschede, the Netherlands

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ABSTRACT

Background: Stroke survivors often show reduced walking velocity and gait asymmetry. These gait abnormalities are associated with reduced propulsion of the paretic leg. This review aimed to provide an overview of the potential effectiveness of post-stroke rehabilitation interventions to improve paretic propulsion, ankle kinetics and walking velocity.

Methods: A systematic search was performed in Pubmed, Web of Science, Embase, and Pedro. Studies were eligible if they reported changes in propulsion measures (impulse, peak value and symmetry ratios) or ankle kinetics (moment and power) following intervention in stroke survivors (group size ≥ 10). Study selection, data extraction and quality assessment were performed independently by two authors.

Findings: A total of 28 studies were included, of which 25 studies applied exercise interventions, two studies focused on surgical interventions, and one on non-invasive brain stimulation. The number of high-quality trials was limited ($N = 6$; score Downs and Black scale ≥ 19). Propulsion measures were the primary outcome in eight studies. In general, mixed results were reported with 14 interventions yielding improvements in propulsion and ankle kinetics. In contrast, gains in walking velocity were observed in the vast majority of studies ($N = 20$ out of 23).

Interpretation: Interventions that yielded gains in propulsion appeared to have in common that they challenged and/or enabled the utilization of latent propulsive capacity of the paretic leg during walking. Walking speed generally increased, regardless of the observed change in propulsion, suggesting the use of compensatory mechanisms. Findings should, however, be interpreted with some caution, as the evidence base for this emerging focus of rehabilitation is limited.

1. Introduction

Improvement of the walking pattern and walking velocity are major rehabilitation goals for individuals post stroke (Bohannon et al., 1988). Approximately 64% of all stroke survivors admitted for inpatient rehabilitation achieve independent walking before being discharged home (Jorgensen et al., 1995). Yet, people after stroke often experience persistent gait abnormalities, such as reduced walking velocity (Olney and Richards, 1996), impaired balance control (Chen et al., 2000) and gait asymmetry (Chen et al., 2005; Patterson et al., 2008). In addition, 'drop foot', 'stiff-knee gait' and circumduction (Balaban and Tok, 2014) are frequently observed following stroke. These gait abnormalities contribute to lower levels of community ambulation and reduced quality of life (Schmid et al., 2007).

Several post-stroke gait abnormalities, like reduced knee flexion during swing (Campanini et al., 2013), reduced step-length symmetry (Balasubramanian et al., 2007), and reduced walking velocity (Hsiao et al., 2016) may be (partly) due to impaired propulsion of the paretic leg. Generation of propulsive forces is one of the essential requirements for walking (Shumway-Cook and Woollacott, 1995). Propulsion contributes to the forward progression of the body and can be derived from the anterior-posterior ground reaction force during walking. The two most important factors associated with the production of propulsion are the ankle plantarflexion moment and the posterior orientation of the center of pressure relative to the position of the center of mass (Peterson et al., 2010). In stroke survivors, the generated propulsive forces are generally lower than those reported in healthy adults (Chen et al., 2005), and the propulsive force of the paretic limb is often

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* Corresponding author at: Sint Maartenskliniek Research, PO BOX 9011, 6500 GM Nijmegen, the Netherlands.
E-mail address: j.alingh@maartenskliniek.nl (J.F. Alingh).

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smaller than that of the non-paretic leg (Bowden et al., 2006). Accordingly, interventions targeting paretic propulsion have the potential to improve the walking pattern post stroke.

In the past years, an increasing number of studies have been published that assessed changes in paretic propulsion in stroke survivors following interventions. The primary objective of this systematic review was to provide an overview of the potential effectiveness of these rehabilitation interventions for improving propulsion outcomes and ankle kinetics during walking. As improvements in paretic propulsion may result in increased walking velocity, the secondary aim of this review was to assess the effectiveness of these interventions on walking velocity.

2. Methods

This systematic review was conducted following the PRISMA statement (Liberati et al., 2009). Since the PRISMA statement is designed for systematic reviews and meta-analysis of intervention studies, we only addressed the items related to systematic reviews.

2.1. Eligibility criteria

To be included in the review process, each study had to meet the following criteria:

1) Type of participants: Adult participants (> 18 years of age) suffering from an ischemic or hemorrhagic stroke in the acute (≤ 1 week post stroke ; Bernhardt et al., 2017), subacute (first week until 6 months post stroke ;Bernhardt et al., 2017) or chronic phase (> 6 months post stroke ;Bernhardt et al., 2017). Studies were excluded if the study was conducted in the (sub)acute phase after stroke, without inclusion of a control group, as uncontrolled study designs in this post-stroke stage do not allow distinguishing interventions effects from changes due to spontaneous recovery. Studies were only considered for inclusion if data of 10 or more people with stroke were reported.
2) Type of intervention: Studies involving single or repeated intervention sessions, without restrictions with regard to the type or intensity of the intervention.
3) Comparison: Studies comparing the pre- to post-intervention changes in outcomes within and/or between each intervention group. Studies were excluded if the changes in outcomes were not statistically tested, or if the pre- and post-intervention measurement were conducted under different circumstances (for example, when an ankle-foot orthosis was worn during the post-intervention measurement but not during the pre-intervention measurement).
4) Outcome measures: Propulsion of the paretic leg during walking measured as primary or secondary outcome of the study. Propulsion measures included:
   a. Propulsive impulse, defined as the time integral of the positive anterior ground reaction force of the paretic leg during the stance phase of gait.
   b. Propulsion symmetry, defined as the propulsive impulse of the paretic leg divided by the sum of the propulsive impulse of the paretic and non-paretic leg.
   c. Peak propulsive force, defined as the maximal positive anterior ground reaction force of the paretic leg during the stance phase of gait.

   In order to provide a complete overview of potentially effective interventions, we chose to also include studies reporting ankle kinetics, as these measures are related to propulsion (Olney et al., 1991; Peterson et al., 2010):
   a. Peak ankle moment, defined as the maximum ankle plantarflexion moment during the stance phase of gait.
   b. Peak ankle power, defined as the maximum value of the cross product of the ankle plantarflexion moment and the angular velocity of the paretic leg during the stance phase of gait.

   Electromyographic activity of the calf muscles, and range of motion of the lower limb joints were not considered as outcome measures of propulsion.
5) Language: studies had to be written in English, German, or the Dutch language.

No restrictions on publication date were imposed.

2.2. Information sources

Studies were selected from electronic database searches and additional scanning of the article reference lists. The electronic database search was applied to Pubmed (1809–Present), Web of Science (1945–Present), Embase (1974–Present), and the Pedro database (1929–Present). The literature search was conducted by the first author (JA) on May 8th 2019. Studies were excluded from the review if no full text paper was available online or provided upon author request.

2.3. Search strategy

The following search terms were used to select studies from the Pubmed database:

(*cerebrovascular disorders* [*mesh*] *OR paresis* [*mesh] OR hemiplegia* [*mesh*] *OR stroke OR cva OR cerebrovascular*) *AND* (*rehabilitation* [*mesh*] *OR exercise* [*mesh*] *OR therapeutics* [*mesh*] *OR intervention OR training OR therapy OR rehabil**) *AND* (*walking* [*mesh*] *OR lower extremity* [*mesh*] *OR walking OR gait*) *AND* (*propulsion OR propulsive OR ground reaction force OR GRF OR* (*kinetic* AND force*)).

A detailed description of the search strategies used in all different databases is presented in Appendix 1.

2.4. Study selection

First, duplicates were manually removed from the search based on title, journal, and author information. Second, title and abstract of the retrieved studies were screened for eligibility. Assessment of eligibility was performed independently by two reviewers (JA, BG). If a study had the potential to be included, the full text article was screened before definitive inclusion. Reference lists and citations of the selected studies were checked to identify additional relevant studies. Disagreement between reviewers was resolved by consensus or after consulting a third assessor (VW).

2.5. Data collection

Data were extracted from the studies by reviewer 1 (JA) and then checked by reviewer 2 (BG). Disagreement between reviewers was resolved by consensus. Four authors were contacted to request additional information regarding the outcome data, of which two authors responded to our request. None provided additional numerical data. The following information was extracted from the included studies:

1) Author and year of publication
2) Study design
3) Participant characteristics: number of post-stroke participants, age and time post stroke in the experimental and (if applicable) control group.
4) Type of intervention: type, duration and frequency of the applied rehabilitation intervention and (if applicable) control treatment. Interventions were either classified as ‘Exercise interventions’ when the intervention included walking or other physical exercises, or as ‘Other interventions’ when the intervention did not primarily involve physical exercises.
5) Type of outcome measures: type of propulsion or ankle kinetics measures investigated.

6) Effect of intervention on propulsion or ankle kinetics measures: mean difference in each propulsion or ankle kinetics measure between the pre and post measurement. If available, the change in each outcome measure was extracted between the pre and follow-up measurement and between experimental groups. Mean differences were categorized as statistically significant increase (+), significant decrease (−), or non-significant change (=). If outcome parameters were not included in the study protocol, or data was not provided after author request, the intervention effects were expressed as 'Not applicable' (NA) or 'Not reported' (NR), respectively. For controlled studies conducted in the (sub)acute phase after stroke, changes in propulsion or ankle kinetics measures between the pre and post or follow-up measurement within each group are shown in grey in the tables, as these changes may be (partly) due to spontaneous recovery. Studies that included a propulsion measure as the primary outcome are shown in bold in the tables.
7) Effect of intervention on walking velocity: walking velocity was used as secondary outcome measure in this review, defined as the self-selected, comfortable walking speed. If available, the mean difference in walking velocity between the pre and post measurements was extracted. Mean differences were categorized as statistically significant increase (+), significant decrease (−), or non-significant change (=). If walking velocity was not measured according to the study protocol, or data was not provided after author request, the intervention effect was expressed as 'Not applicable' (NA) or 'Not reported' (NR), respectively.

2.6. Quality assessment

To globally assess the quality of the included studies, the Downs and Black scale (Downs and Black, 1998) was used. This scale consists of 27 items which provide insight into the reporting quality, external validity, internal validity (bias and confounding) and power. Item 27 was slightly modified, to score the availability of a power analysis (see Appendix 2 for the complete scale). Scores ranged from 0 to 28, and a study with a total score of 19 or more (> 66%) was considered to be of high quality (Willems et al., 2015). Assessment of study quality was performed independently by two reviewers (JA, BG), with disagreement between reviewers being resolved by consensus or after consulting a third assessor (VW).

3. Results

3.1. Study selection

The search in the electronic databases identified a total of 1061 citations, of which 659 unique citations remained after adjusting for duplicates. A total of 28 studies met the eligibility criteria and were included in this review (Awad et al., 2014; Betschart et al., 2018; Bonnyaud et al., 2013a; Bonnyaud et al., 2013b; Bonnyaud et al., 2014; Carda et al., 2009; Carda et al., 2010; Combs et al., 2012; De Luca et al., 2018; Forrester et al., 2016; Hase et al., 2011; Hsiao et al., 2016; Jonsdottir et al., 2010; Kesar et al., 2015; Lauziere et al., 2014; Lewek et al., 2018; Mao et al., 2015; Milot et al., 2013; Mirelman et al., 2010; Palmer et al., 2017; Reisman et al., 2013; Richards et al., 2004; Routson et al., 2013; Sheffler et al., 2015; Teixeira-Salmela et al., 2001; van Asseldonk and Boonstra, 2016; Yavuzer et al., 2006; Yeung et al., 2018). An overview of the selection procedure is provided in the flowchart (Fig. 1).

3.2. Study characteristics

Characteristics of the 28 included studies are shown in Table 1. They consisted of 12 randomized controlled trials (Bonnyaud et al., 2013a; Bonnyaud et al., 2013b; Bonnyaud et al., 2014; Forrester et al., 2016; Jonsdottir et al., 2010; Mao et al., 2015; Milot et al., 2013; Mirelman et al., 2010; Richards et al., 2004; Sheffler et al., 2015; Yavuzer et al., 2006; Yeung et al., 2018), two randomized cross-over trial (Palmer et al., 2017; van Asseldonk and Boonstra, 2016), one non-randomized controlled trial (Hase et al., 2011), one non-randomized cross-over trial (Lauziere et al., 2014), seven pre-post studies without follow-up (De Luca et al., 2018; Hsiao et al., 2016; Kesar et al., 2015; Lewek et al., 2018; Reisman et al., 2013; Routson et al., 2013; Teixeira-Salmela et al., 2001), and five pre-post studies with follow-up (Awad et al., 2014; Betschart et al., 2018; Carda et al., 2009; Carda et al., 2010; Combs et al., 2012). Overall, 25 studies were classified as 'Exercise interventions' (Awad et al., 2014; Betschart et al., 2018; Bonnyaud et al., 2013a; Bonnyaud et al., 2013b; Bonnyaud et al., 2014; Combs et al., 2012; De Luca et al., 2018; Forrester et al., 2016; Hase et al., 2011; Hsiao et al., 2016; Jonsdottir et al., 2010; Kesar et al., 2015; Lauziere et al., 2014; Lewek et al., 2018; Mao et al., 2015; Milot et al., 2013; Mirelman et al., 2010; Palmer et al., 2017; Reisman et al., 2013; Richards et al., 2004; Routson et al., 2013; Sheffler et al., 2015; Teixeira-Salmela et al., 2001; Yavuzer et al., 2006; Yeung et al., 2018), of which eight studies reported propulsion as a primary outcome measure (Awad et al., 2014; Combs et al., 2012; Forrester et al., 2016; Hase et al., 2011; Hsiao et al., 2016; Kesar et al., 2015; Lewek et al., 2018; Reisman et al., 2013). Three studies were classified as 'Other interventions' (Carda et al., 2009; Carda et al., 2010; van Asseldonk and Boonstra, 2016), of which none reported propulsion as a primary outcome. Eight studies consisted of single-session training interventions (Bonnyaud et al., 2013a; Bonnyaud et al., 2013b; Bonnyaud et al., 2014; Kesar et al., 2015; Lauziere et al., 2014; Lewek et al., 2018; Palmer et al., 2017; van Asseldonk and Boonstra, 2016), 18 studies involved interventions with multiple training sessions (Awad et al., 2014; Betschart et al., 2018; Combs et al., 2012; De Luca et al., 2018; Forrester et al., 2016; Hase et al., 2011; Hsiao et al., 2016; Jonsdottir et al., 2010; Mao et al., 2015; Milot et al., 2013; Mirelman et al., 2010; Reisman et al., 2013; Richards et al., 2004; Routson et al., 2013; Sheffler et al., 2015; Teixeira-Salmela et al., 2001; Yavuzer et al., 2006; Yeung et al., 2018), and two studies concerned surgical interventions (Carda et al., 2009; Carda et al., 2010). The number of included participants ranged from 10 (van Asseldonk and Boonstra, 2016) to 177 (Carda et al., 2009), with 26 studies being performed in the chronic phase (Awad et al., 2014; Betschart et al., 2018; Bonnyaud et al., 2013a; Bonnyaud et al., 2013b; Bonnyaud et al., 2014; Carda et al., 2009; Carda et al., 2010; Combs et al., 2012; De Luca et al., 2018; Forrester et al., 2016; Hase et al., 2011; Hsiao et al., 2016; Jonsdottir et al., 2010; Kesar et al., 2015; Lauziere et al., 2014; Lewek et al., 2018; Milot et al., 2013; Mirelman et al., 2010; Palmer et al., 2017; Reisman et al., 2013; Routson et al., 2013; Sheffler et al., 2015; Teixeira-Salmela et al., 2001; van Asseldonk and Boonstra, 2016; Yavuzer et al., 2006; Yeung et al., 2018) and two studies in the subacute phase after stroke (Mao et al., 2015; Richards et al., 2004). Outcome measures for propulsion or ankle kinetics varied across studies, with peak propulsive force being reported most frequently ($N = 11$), followed by propulsive impulse ($N = 8$), peak ankle plantarflexion moment (N = 8), peak ankle plantarflexion power (N = 8) and propulsion symmetry ($N = 6$). Effects on walking velocity were reported in 23 studies (Awad et al., 2014; Betschart et al., 2018; Bonnyaud et al., 2013a; Bonnyaud et al., 2013b; Bonnyaud et al., 2014; Carda et al., 2009; Carda et al., 2010; Combs et al., 2012; De Luca et al., 2018; Forrester et al., 2016; Hase et al., 2011; Hsiao et al., 2016; Jonsdottir et al., 2010; Mao et al., 2015; Milot et al., 2013; Mirelman et al., 2010; Reisman et al., 2013; Richards et al., 2004; Routson et al., 2013; Sheffler et al., 2015; Teixeira-Salmela et al., 2001; Yavuzer et al., 2006; Yeung et al., 2018).

3.3. Quality assessment

Results of the quality assessment according to the Downs and Black scale are shown in Table 2. Six studies, which were all randomized controlled trials, were classified as having a high quality (Jonsdottir

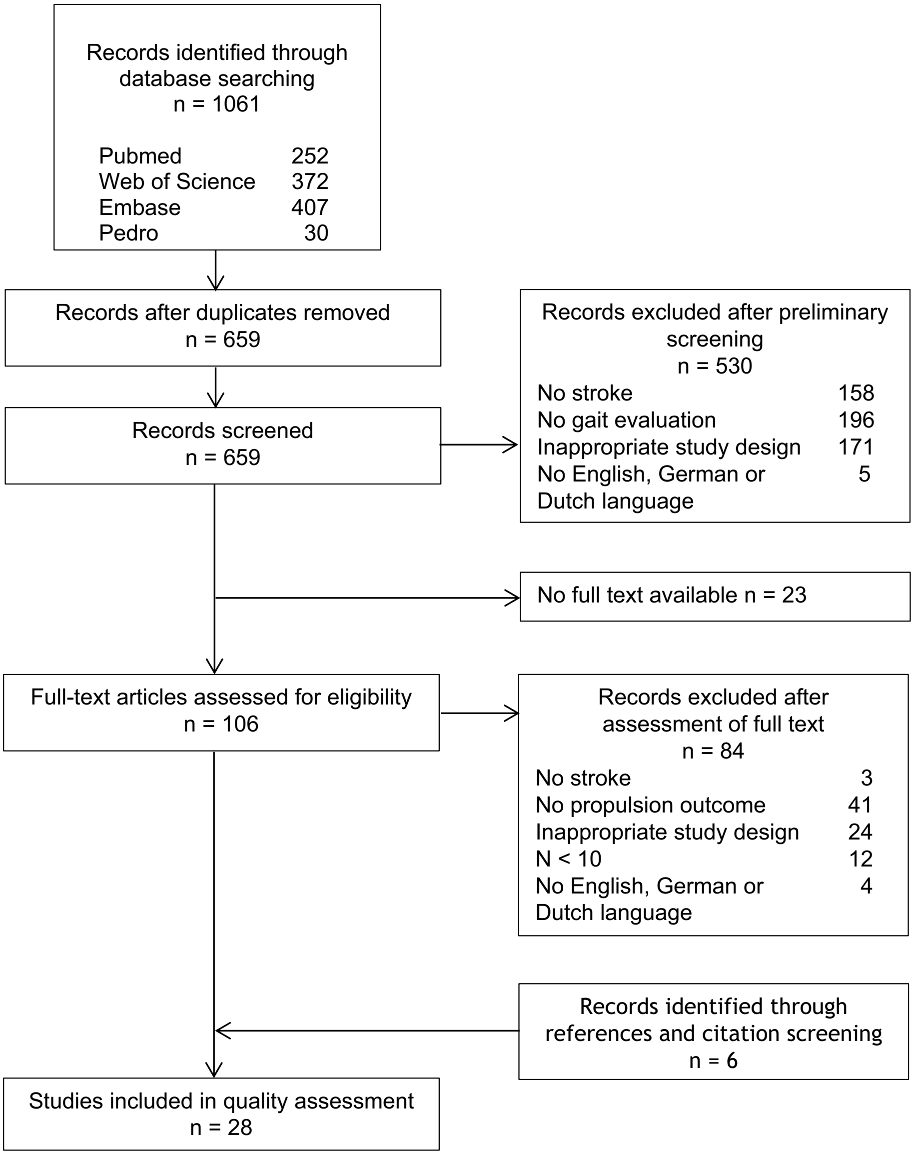

Fig. 1. Flowchart.

et al., 2010; Mao et al., 2015; Milot et al., 2013; Mirelman et al., 2010; Richards et al., 2004; Yeung et al., 2018). More than 90% of all studies ($N \geq 26$) clearly described the main outcome (item 2), patient characteristics (item 3), intervention (item 4) and main findings (item 6). Regarding the external validity, items concerning the representativeness of the study sample (items 11 and 12) could not be judged for any of the studies.

3.4. Exercise interventions

3.4.1. Treadmill gait training

Seven studies investigated the effect of treadmill training on paretic propulsion (Bonnyaud et al., 2013a; Combs et al., 2012; Lewek et al., 2018; Routson et al., 2013) or ankle kinetics (Betschart et al., 2018; Bonnyaud et al., 2013a; Combs et al., 2012; Lauziere et al., 2014; Lewek et al., 2018; Mao et al., 2015; Routson et al., 2013), using body weight supported treadmill training (Combs et al., 2012; Mao et al., 2015; Routson et al., 2013), training on a split-belt treadmill (Betschart et al., 2018; Lauziere et al., 2014), regular treadmill training (Bonnyaud et al., 2013a), or treadmill walking with an impeding force applied to the pelvis (Lewek et al., 2018). Two studies were randomized controlled trials (Bonnyaud et al., 2013a; Mao et al., 2015). In two studies propulsion was measured as the primary outcome (Combs et al., 2012; Lewek et al., 2018). Six studies were performed in the chronic phase (Betschart et al., 2018; Bonnyaud et al., 2013a; Combs et al., 2012; Lauziere et al., 2014; Lewek et al., 2018; Routson et al., 2013) and only one study was performed in the subacute phase after stroke (Mao et al., 2015). Three studies evaluated a single session of gait training (Bonnyaud et al., 2013a; Lauziere et al., 2014; Lewek et al., 2018) and four studies evaluated multiple training sessions (Betschart et al., 2018; Combs et al., 2012; Mao et al., 2015; Routson et al., 2013).

Propulsion measures did not differ between pre and post intervention in two studies involving repeated sessions of body weight supported treadmill training (Combs et al., 2012; Routson et al., 2013). Significant improvements in propulsion measures were only observed in studies involving a single training session that did not include body weight support. A single session of treadmill walking with a backward-oriented impeding force applied to the pelvis improved propulsive symmetry, propulsive impulse and peak propulsive force (Lewek et al., 2018). A single session of regular treadmill training without body weight support also showed improvements in peak propulsive force, but this effect was only evident at 20 min retention and not directly

Table 1

Characteristics of the studies included in this review. Detailed descriptions of the study population, intervention and outcome measures on propulsion, ankle kinetics and walking velocity are reported. Studies that included a propulsion measure as the primary outcome are shown in bold. Data is only reported for stroke survivors who participated in the experimental (E) or control (C) group. Outcomes are categorized as significant increase (+), significant decrease (−), or non-significant change (=) between the pre- and post-measurement, between the pre- and follow-up measurement, and between the experimental and control group. For studies conducted in the subacute phase after stroke, the outcomes between the pre- and post- or follow-up measurement are shown in grey. Apart from propulsion symmetry, the propulsion measures and ankle kinetics are solely reported for the paretic limb. Study quality is assessed with the Downs and Black scale. Detailed information about the Downs and Black scale can be found in Appendix 2. Time since stroke is reported in days (d.), weeks (wk.), months (mo.), or years (yr.).

	Type of intervention	Study			Population			Intervention		Outcomes				Velocity outcomes
		Author	Design	High study quality	N	Age in years (mean (SD))[a]	Time since stroke (mean (SD))[a]	Single session, training or surgery	Description and duration	Propulsion measures *Ankle kinetics*	Change pre-post	Change pre-follow-up	Group comparison	Change pre-post
Exercise	Treadmill gait training	Mao et al., 2015	RCT	Yes	24	E: 59.6 (9.2) C: 60.8 (10.7)	E: 49.3 d. (19.5) C: 47.7 d. (16.8)	Training	3 weeks E) body weight supported treadmill training or C) conventional gait training (5 times a week, 20–40 min)	*Peak ankle moment*	= (E) = (C)	NA	NA	+ (E) = (C)
		Bonnyaud et al., 2013a	RCT	No	26	E: 52.5 (12.3) C: 47.7 (9.8)	E: 4.2 yr. (3.3) C: 6.2 yr. (4.1)	Single session	Single session of E) treadmill training or C) overground training (20 min)	Peak propulsive force	=	+ (20 min.)	E = C	+
		Combs et al., 2012	Pre-post	No	15	59.9 (11.2)	3.8 yr. (3.2)	Training	8 weeks body weight supported treadmill training (3 times a week, 20 min)	Propulsion symmetry Propulsive impulse	= =	= (6 mo.) = (6 mo.)	NA	+
		Routson et al., 2013	Pre-post	No	27	57.3 (13.2)	19.0 mo. (13.0)	Training	12 weeks body weight supported treadmill training with manual support (3 times a week, 20 min) followed by overground walking (10–20 min)	Propulsion symmetry	=	NA	NA	+
		Lewek et al., 2018	Pre-post	No	10	60 (16)	105 mo. (127)	Single session	Single session of walking on a treadmill against an impeding force applied to the body's center of mass (3 min)	Propulsive symmetry Propulsive impulse Peak propulsive force	+ + +	NA	NA	NA
		Betschart et al., 2018	Pre-post	No	12	53.3 (8.7)	25.1 mo. (23.5)	Training	2 weeks error-augmentation-based split belt treadmill walking with the leg with the shorter steplength walking on the faster belt (2–3 times a week, 20 min)	*Peak ankle moment*	=	=	NA	+
		Lauziere et al., 2014	Cross-over	No	20	49.3 (13.2)	> 6 mo.	Single session	Single session of split belt treadmill walking at comfortable speed, with E1) paretic leg on faster belt and E2) non-paretic leg on faster belt (6 min)	*Peak ankle moment*	− (E1) + (E2)	NA	E1 < E2	NA
	Gait training with functional electrical stimulation	Sheffler et al., 2015	RCT	No	1-10	E: 52.8 (12.2) C: 53.2 (10.1)	E: 44.7 mo. (97.5) C: 44.9 mo. (79.2)	Training	12 weeks E) training with a surface peroneal nerve stimulator (5 week, 2 times a week, 60 min & 7 week, 3 times a week, 60 min) or C) conventional care	Peak propulsive force *Peak ankle power*	+ +	= (12 wk.) + (24 wk.) + (12 wk.) + (24 wk.)	E = C E = C	+
		Awad et al., 2014	Pre-post	No	13	61 (8.3)	3.2 yr. (3.1)	Training	12 weeks training at fast speed with FES delivered to both	Propulsion symmetry Propulsive	+ + +	+ (3 mo.) = (3 mo.) + (3 mo.)	NA	+

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Table 1 (*continued*)

Type of intervention	Study			Population			Intervention		Outcomes				Velocity outcomes
	Author	Design	High study quality	N	Age in years (mean (SD))[a]	Time since stroke (mean (SD))[a]	Single session, training or surgery	Description and duration	Propulsion measures *Ankle kinetics*	Change pre-post	Change pre-follow-up	Group comparison	Change pre-post
								dorsal- and plantarflexors (3 times a week, 30 min)	impulse Peak propulsive force				
	Hsiao et al., 2016	Pre-post	No	45	58.3 (11.8)	4.5 yr. (6.5)	Training	12 weeks training at E1) fastest speed or E2) fast speed with FES delivered to both dorsal- and plantarflexors or C) self-selected speed (3 times a week, 36 min)	Peak propulsive force	+ (score E1, E2 & C combined)	NA	NR	+ (score E1, E2 & C combined)
	Reisman et al., 2013	Pre-post	No	13	61 (8.3)	38.7 mo. (35.2)	Training	12 weeks treadmill training at fast speed with FES delivered to both dorsal- and plantarflexors (3 times a week, 30 min)	Propulsive impulse; Peak propulsive force	+ (pre-4 wk.) = (4–12 wk.) + (pre-4 wk.) = (4–12 wk.)	NA	NA	+
	Kesar et al., 2015	Pre-post	No	13	61.3 (9.6)	29.1 mo. (29.0)	Single session	Single session of walking at fast speed with FES delivered to both dorsal- and plantarflexors (30 min)	Propulsive impulse Peak propulsive force	+ +	NA	NA	NA
	Palmer et al., 2017	Randomized cross-over	No	20	59.5 (12.0)	42 mo. (35)	Single session	Single session of walking at self-selected speed E1) with or E2) without FES delivered to both dorsal- and plantarflexors (30 min)	*Peak ankle moment*	= (E1) = (E2)	NA	NA	NA
Gait training according to modified constraint induced movement therapy	Bonnyaud et al., 2013b	RCT	No	60	50.3 (13.1)	5.7 yr. (6.3)	Single session	Single session of E1) overground training with mass attached to the nonparetic ankle, C1) overground training without mass, E2) treadmill training with mass attached to the nonparetic ankle or C2) treadmill training without mass (20 min)	Peak propulsive force	=	= (20 min.)	E1 = C1 E2 = C2	=
	Bonnyaud et al., 2014	RCT	No	26	E: 52.1 (13.8) C: 49.1 (9.5)	E: 7.8 yr. (11.8) C: 5.5 yr. (4.7)	Single session	Single session of E) Lokomat constraint gait training or C) Lokomat conventional gait training (20 min)	Peak propulsive force	=	+ (20 min.)	E = C	+
	Hase et al., 2011	Non RCT	No	22	E: 60.1 (13.0) C: 62.3 (9.2)	E: 36.4 mo. (25.1) C: 44.1 mo. (29.4)	Training	3 weeks E) prosthetic gait training or C) treadmill training (3–5 times a week, 10–15 min)	Propulsive impulse	NR	NA	E > C	C = E
Gait training with robotics	**Forrester et al., 2016**	RCT	No	26	E: 59.5 (3.6) C:56.8 (3.2)	E: 37.4 mo. (10.4) C:34.0 mo. (6.8)	Training	6 weeks E) treadmill-integrated ankle robotics training or C) seated ankle robotics training (3 times a week, 60 min)	Propulsive impulse	+ (E) = (C)	+ (E, 6 wk.) = (C, 6 wk.)	E > C	+ (E) = (C)
	Yeung et al., 2018	RCT	Yes	19	E: 54.2 (13.0) C: 61.2 (10.6)	E: 4.4 yr. (2.5) C: 6.0 yr. (4.5)	Training	5 weeks of overground gait training with E) a robot-assisted ankle foot orthosis assisting dorsiflexion during overground walking and a combination of	Peak propulsive force	= (E) = (C)	NA	E = C	+ (E) = (C)

(*continued on next page*)

Table 1 (*continued*)

	Type of intervention	Study			Population			Intervention		Outcomes				Velocity outcomes
		Author	Design	High study quality	N	Age in years (mean (SD))[a]	Time since stroke (mean (SD))[a]	Single session, training or surgery	Description and duration	Propulsion measures *Ankle kinetics*	Change pre-post	Change pre-follow-up	Group comparison	Change pre-post
									plantar- and dorsiflexion during stair climbing or C) the ankle foot orthosis without robot assistance (2–4 times a week, 30–60 min)					
		De Luca et al., 2018	Pre-post	No	12	62.75 (12.29)	6.41 yr. (4.39)	Training	5–7 weeks of robot-assisted training with an endpoint robot (3 times a week, 45 min)	*Peak ankle power*	+	NA	NA	+
	Movement training with feedback	Mirelman et al., 2010	RCT	Yes	18	62 (range 41–75)	> 2 yr.	Training	4 weeks ankle movement training E) with virtual reality or C) without virtual reality (3 times a week, 60 min)	*Peak ankle moment* *Peak ankle power*	NR	NR (3 mo.)	E > C (BF) E = C (SH) E > C (BF) E = C (SH)	+ (E) = (C)
		Jonsdottir et al., 2010	RCT	Yes	20	E: 61.6 (13.1) C: 62.6 (9.5)	E: 5.9 yr. (10.5) C: 1.8 yr. (0.9)	Training	7 weeks of overground gait training with E) task-oriented EMG biofeedback recorded from the gastrocnemius lateralis or C) conventional rehabilitation (3 times a week, 45 min)	*Peak ankle power*	+ (E) = (C)	+ (E) = (C)	NA	+ (E) = (C)
	Strength and conditioning training	Milot et al., 2013	RCT	Yes	30	E: 58.5 (14.9) C: 54.7 (14.6)	E: 56.9 mo. (43.8) C: 85.5 mo. (111.9)	Training	6 weeks task-specific isokinetic strengthening program of the E) affected lower-limb muscles C) affected upper-limb muscles (3 times a week, 60–90 min)	*Peak ankle power*	= (E) = (C)	NA	NA	+ (E) + (C)
		Teixeira-Salmela et al., 2001	Pre-post	No	13	67.7 (9.2)	7.7 yr. (9.4)	Training	10 weeks muscle strength and physical conditioning program (3 times a week, 60–90 min) with additional home-exercises (3 times a week)	*Peak ankle moment* *Peak ankle power*	= =	NA	NA	+
	Balance training	Yavuzer et al. [2006]	RCT	No	41	E: 59.8 (11.6) C: 62.1 (12.0)	E: 11.1 mo. (24.6) C: 5.5 mo. (3.5)	Training	8 weeks E) conventional rehabilitation (5 times a week, 2–5 h/day) combined with 3 weeks balance training (5 times a week, 15 min/day) or C) conventional rehabilitation (5 times a week, 2–5 h/day)	*Peak ankle moment*	= (E) = (C)	NA	E = C	=
	Training with technology	Richards et al. [2004]	RCT	Yes	63	E: 62.9 (12) C: 60.7 (12)	52.0 d. (22) 52.6 d. (18)	Training	8 weeks of E) task-oriented gait training using rehabilitation technology such as treadmills, isokinetic dynamometers or limb load monitors or C) conventional rehabilitation (5 times a week, 60 min)	*Peak ankle power*	+ (E) + (C)	NA	E = C	+ (E) + (C)
Other	Surgical elongation or transfer of the calf muscle-tendon complex	Carda et al. [2009]	Pre-post	No	1-77	49.7 (14.0)	5.6 yr. (7.5)	Surgery	Surgical correction of equinovarus foot deformity	Propulsion symmetry Peak propulsive force *Peak ankle moment*	NA	+ (1 yr.) + (1 yr.) − (1 yr.) − (1 yr.)	NA	+

(*continued on next page*)

Table 1 (*continued*)

Type of intervention	Study			Population			Intervention		Outcomes				Velocity outcomes
	Author	Design	High study quality	N	Age in years (mean (SD))[a]	Time since stroke (mean (SD))[a]	Single session, training or surgery	Description and duration	Propulsion measures *Ankle kinetics*	Change pre-post	Change pre-follow-up	Group comparison	Change pre-post
									Peak ankle power				
	Carda et al. [2010]	Pre-post	No	29	E1: 51.2 (range 32.4–70.4) E2: 50.3 (range 20–67)	E1: 6.8 yr. (range 1.6–13.7) E2: 5.1 yr. (range 1.2–10.3)	Surgery	Surgical correction of equinovarus foot deformity using E1) extensor hallucis longus transfer or E2) split transfer of the tibialis anterior tendon	Propulsion symmetry	NA	+ (E1, 1 yr.) + (E2, 1 yr.)	E1 = E2	+
Transcranial direct current stimulation	van Asseldonk and Boonstra [2016]	Randomized cross-over	No	10	58.0 (11.1)	44.7 mo. (35.8)	Single session	Single session of E1) unihemispheric tDCS, E2) dual hemispheric tDCS and C) sham stimulation (10 min, each condition performed 1 week apart)	Propulsive impulse	= (E1) = (E2) = (C)	= (E1, 45 min.) = (E2, 45 min.) = (C, 45 min.)	E1 = E2 = C	NA

Abbreviations: electromyography (EMG), functional electrical stimulation (FES), transcranial direct current stimulation (tDCS), not applicable (NA), not reported (NR), walking barefoot (BF), walking with shoes and orthotics (SH).

[a] Unless stated otherwise.

following the intervention (Bonnyaud et al., 2013a). There was, however, no superior gain in propulsion following regular treadmill compared to overground gait training, as both interventions resulted in similar effects on paretic propulsion (Bonnyaud et al., 2013a).

Neither for ankle kinetics (Mao et al., 2015) nor for propulsion measures (Combs et al., 2012; Routson et al., 2013), there was any effect of repeated sessions of body weight supported treadmill training. In addition, split-belt treadmill training with the leg with the shortest step length walking on the fast belt did not affect ankle kinetics (Betschart et al., 2018). However, a single session of 6 min split-belt treadmill training with the non-paretic leg walking on the fast belt did yield improvements in peak ankle moment (Lauziere et al., 2014). Despite the varying effects of the interventions on propulsion and ankle kinetics, walking velocity increased in five studies (Betschart et al., 2018; Bonnyaud et al., 2013a; Combs et al., 2012; Mao et al., 2015; Routson et al., 2013).

3.4.2. *Gait training with functional electrical stimulation*

Six studies examined the effect of functional electrical stimulation (FES) on propulsion measures (Awad et al., 2014; Hsiao et al., 2016; Kesar et al., 2015; Reisman et al., 2013; Sheffler et al., 2015) or ankle kinetics (Palmer et al., 2017; Sheffler et al., 2015) in chronic stroke survivors, applying stimulation to the peroneal nerve during walking at a comfortable velocity (Sheffler et al., 2015) or to both ankle dorsiflexors and plantarflexors during walking at a comfortable (Palmer et al., 2017) or fast velocity (Awad et al., 2014; Hsiao et al., 2016; Kesar et al., 2015; Reisman et al., 2013). Two studies evaluated the training effect after a single session (Kesar et al., 2015; Palmer et al., 2017), whereas four studies evaluated the effect after multiple training sessions (Awad et al., 2014; Hsiao et al., 2016; Reisman et al., 2013; Sheffler et al., 2015), of which one study involved a randomized controlled trial (Sheffler et al., 2015). Except for the studies of Sheffler et al., (2015) and Palmer et al., (2017), propulsion was measured as the primary outcome in all FES studies.

Five out of the six studies reported improvements in paretic propulsion immediately after single (Kesar et al., 2015) or multiple training sessions with FES compared to pre intervention (Awad et al., 2014; Hsiao et al., 2016; Reisman et al., 2013; Sheffler et al., 2015), four of which combined FES with walking at faster than comfortable velocity (Awad et al., 2014; Hsiao et al., 2016; Kesar et al., 2015; Reisman et al., 2013). Some improvements in propulsion were retained at 3 months follow-up (Awad et al., 2014; Sheffler et al., 2015), whereas other propulsion measures returned to baseline levels (Awad et al., 2014; Sheffler et al., 2015; see Table 1). One of these studies compared the effect of electrical stimulation of the ankle dorsiflexors with usual care, and this study did not show superior gains in paretic propulsion with FES (Sheffler et al., 2015).

In agreement with the results for propulsion measures, ankle kinetics improved following multiple training sessions with FES delivered to the peroneal nerve (Sheffler et al., 2015). In contrast, no gains in ankle kinetics were observed in one study after a single session with FES delivered to both ankle dorsiflexors and plantarflexors during walking at a comfortable velocity (Palmer et al., 2017). Four studies reported an increase in walking velocity after the intervention (Awad et al., 2014; Hsiao et al., 2016; Reisman et al., 2013; Sheffler et al., 2015).

3.4.3. *Modified constraint-induced movement therapy*

Three studies evaluated the modified constraint-induced movement therapy approach to train paretic propulsion in individuals with chronic stroke (Bonnyaud et al., 2013b; Bonnyaud et al., 2014; Hase et al., 2011), one of which focused on propulsion as the primary outcome (Hase et al., 2011). Two randomized controlled trials concerned a single session (Bonnyaud et al., 2013b; Bonnyaud et al., 2014), and one study concerned multiple training sessions (Hase et al., 2011). Three weeks of constraint-induced movement therapy using a ‘dummy prosthesis’ (a below-knee prosthesis to simulate amputee gait, holding the leg in a 90°

Table 2

Quality assessment of exercise and other interventions according to the Downs and Black scale. Each item was scored 0 to 1 point, except for item 5 (score 0 to 2 points), resulting in a maximum score of 28 points. Study quality is considered to be high if the total score was 19 points or more. Studies that included a propulsion measure as the primary outcome are shown in bold.

	Type of intervention	Study	Reporting										External validity			Internal validity – Bias							Internal validity – confounding						Power	Total
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	
Exercise	Treadmill gait trainingGait training with functional electrical stimulation	Mao et al., 2015	1	1	1	1	1	1	1	0	0	1	0	0	1	0	1	1	1	0	1	1	1	1	1	0	1	1	0	19
		Bonnyaud et al., 2013a	1	1	1	1	1	1	1	0	0	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	0	0	0	17
		Combs et al., 2012	1	1	1	1	0	1	1	0	0	1	0	0	1	0	0	1	1	1	1	1	0	0	0	0	0	0	0	13
		Routson et al., 2013	1	1	1	1	0	1	1	0	1	1	0	0	1	0	0	1	1	1	0	1	0	0	0	0	0	1	0	14
		Lewek et al., 2018	1	1	1	1	0	1	1	0	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	0	14
		Betschart et al., 2018	1	1	1	1	0	1	1	0	1	1	0	0	1	0	0	1	1	1	1	1	0	0	0	0	0	1	0	15
		Lauziere et al., 2014	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	8
	Gait training with functional electrical stimulation	Sheffler et al., 2015	0	1	1	1	2	1	1	0	0	1	0	0	0	0	0	1	1	1	0	1	1	1	1	0	1	1	1	18
		Awad et al., 2014	1	1	1	1	0	1	1	1	0	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	13
		Hsiao et al., 2016	0	1	1	1	0	1	1	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	1	0	10
		Reisman et al., 2013	1	1	1	1	0	1	1	0	0	0	0	0	0	0	1	1	1	0	1	1	0	0	0	0	0	0	0	11
		Kesar et al., 2015	1	1	1	1	0	1	1	0	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	0	14
		Palmer et al., 2017	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	0	1	0	0	18
	Gait training according to modified constraint induced movement therapy	Bonnyaud et al., 2013b	0	1	0	1	0	1	1	0	0	1	0	0	1	0	0	1	1	1	1	1	1	1	1	0	0	0	0	14
		Bonnyaud et al., 2014	1	1	1	1	1	1	1	0	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	0	1	0	0	17
	Gait training with robotics	**Hase et al., 2011**	0	1	1	1	1	1	1	0	1	1	0	0	0	0	0	1	1	0	1	1	0	0	0	0	1	1	1	15
		Forrester et al., 2016	1	1	1	1	1	1	0	1	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	0	1	0	0	17
		Yeung et al., 2018	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	1	1	1	1	0	1	1	0	19
		De Luca et al., 2018	1	1	1	1	0	1	1	0	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	0	14
	Movement training with feedback	Mirelman et al., 2010	1	0	1	1	1	1	1	1	1	1	0	0	0	1	0	0	1	1	1	1	1	1	1	0	1	1	0	19
		Jonsdottir et al., 2010	1	1	1	1	1	1	1	0	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	1	0	19
	Strength and conditioning training	Milot et al., 2013	1	1	1	1	1	1	1	0	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	0	1	0	0	19
		Teixeira-Salmela et al., 2001	1	0	1	1	1	1	1	0	1	0	0	0	1	0	0	1	1	1	1	1	0	0	0	0	0	1	0	14
	Balance training	Yavuzer et al., 2006	0	1	1	1	1	1	0	0	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	0	1	1	0	18
	Training with technology	Richards et al., 2004	0	1	1	1	2	1	1	0	1	0	0	0	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	21
Other	Surgical elongation or transfer of the calf muscle-tendon complex	Carda et al., 2009	1	1	1	1	0	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	0	15
		Carda et al., 2010	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	0	1	1	0	1	0	0	1	1	0	16
	Transcranial direct current stimulation	van Asseldonk and Boonstra 2016	0	1	1	1	1	0	0	0	1	1	0	0	0	1	1	1	1	1	0	1	1	1	1	0	1	1	0	17

flexed knee position) at the non-paretic side showed superior gains in paretic propulsion when compared to regular treadmill training (Hase et al., 2011). In contrast, immediately after a single session of modified constraint-induced gait training with a mass attached (Bonnyaud et al., 2013b) or a robotic constraint applied to the non-paretic leg (Bonnyaud et al., 2014) no changes in paretic propulsion were observed compared to pre intervention (Bonnyaud et al., 2013b; Bonnyaud et al., 2014). At 20 min follow-up, paretic propulsion either remained unchanged (Bonnyaud et al., 2013b) or increased relative to pre intervention (Bonnyaud et al., 2014). Neither of these single-session interventions yielded superior effects compared to unconstrained overground or treadmill training (Bonnyaud et al., 2013b; Bonnyaud et al., 2014). The effect of the interventions on walking velocity was ambiguous, with the post-intervention walking velocity being unchanged (Bonnyaud et al., 2013b) or increased (Bonnyaud et al., 2014).

3.4.4. *Gait training with robotics*

Three studies investigated the effect of multiple sessions of robot-assisted gait interventions on propulsion measures (Forrester et al., 2016; Yeung et al., 2018) or ankle kinetics (De Luca et al., 2018) in the chronic phase after stroke. Two studies were randomized controlled trials (Forrester et al., 2016; Yeung et al., 2018), one of which included a propulsion measure as the primary outcome (Forrester et al., 2016). The interventions concerned a treadmill-integrated ankle robotics training (Forrester et al., 2016), overground gait training with a robot-assisted ankle-foot orthosis (Yeung et al., 2018) or robot-assisted gait training with an endpoint robot system (De Luca et al., 2018).

Treadmill-integrated ankle robotics training improved propulsion measures post intervention, with the gains in propulsion being retained at six weeks follow-up (Forrester et al., 2016). These gains in the experimental group were superior to those in the control group, who received seated ankle robotics training (Forrester et al., 2016). In contrast, gait training with a robot-assisted ankle-foot orthosis did not yield improvements in propulsion measures post intervention (Yeung et al., 2018). These findings were similar to walking with a conventional ankle-foot orthosis (Yeung et al., 2018). One study evaluated ankle kinetics following robot-assisted gait training with an endpoint robot system and showed improvements in peak ankle power (De Luca et al., 2018). Walking velocity increased in all experimental groups and remained unchanged in the control groups (De Luca et al., 2018; Forrester et al., 2016; Yeung et al., 2018).

3.4.5. *Other exercise interventions*

The remaining six studies examined the effect of other types of exercise interventions on ankle kinetics, including movement training with feedback (Jonsdottir et al., 2010; Mirelman et al., 2010), strength and conditioning training (Milot et al., 2013; Teixeira-Salmela et al., 2001), balance training (Yavuzer et al., 2006) and training with the use of technology (Richards et al., 2004). None of these studies evaluated propulsion measures. All studies concerned multiple training sessions, of which five studies were randomized controlled trials (Jonsdottir et al., 2010; Milot et al., 2013; Mirelman et al., 2010; Richards et al., 2004; Yavuzer et al., 2006). Five studies were performed in the chronic phase (Jonsdottir et al., 2010; Milot et al., 2013; Mirelman et al., 2010; Teixeira-Salmela et al., 2001; Yavuzer et al., 2006) and one study was performed in the subacute phase after stroke (Richards et al., 2004). Gains in ankle kinetics were observed after movement training with the use of feedback. Biofeedback provided during overground walking improved ankle kinetics, while the control group receiving usual care did not show changes in ankle kinetics (Jonsdottir et al., 2010). The use of virtual reality during seated ankle movement training showed superior gains in ankle kinetics compared to the training without virtual reality when patients walked barefooted, but outcomes were similar for the virtual reality and non-virtual reality group when walking with shoes (Mirelman et al., 2010). In a study that combined conventional rehabilitation with the use of technology (i.e. treadmill, limb load monitor or dynamometer) in individuals in the subacute phase after stroke, gains in ankle kinetics over time were not different between training with and without the use of technology (Richards et al., 2004). Ankle kinetics remained unchanged at posttest after multiple sessions of strength training, with (Teixeira-Salmela et al., 2001) or without (Milot et al., 2013) concurrent conditioning training, or balance training (Yavuzer et al., 2006). Walking velocity increased in five studies (Jonsdottir et al., 2010; Milot et al., 2013; Mirelman et al., 2010; Richards et al., 2004; Teixeira-Salmela et al., 2001), and remained constant in one study (Yavuzer et al., 2006).

3.5. *Other interventions*

Three studies evaluated interventions that did not involve physical exercises, none of which included a propulsion measure as primary outcome. Two studies evaluated the effect of surgical elongation or transfer of the calf muscle-tendon complex on propulsion and ankle kinetics in chronic stroke survivors with equinovarus foot deformity (Carda et al., 2009; Carda et al., 2010). One year after the surgery, propulsion measures improved (Carda et al., 2009; Carda et al., 2010) and the gain in propulsion was similar across different surgical procedures (i.e. plantarflexor lengthening and/or tendon transfers; Carda et al., 2010). Unlike the observed improvement in propulsion measures, ankle kinetics declined 1 year after surgery (Carda et al., 2009). Both studies showed gains in walking velocity 1 year after surgery (Carda et al., 2009; Carda et al., 2010).

The remaining study examined the effect of transcranial direct current stimulation on walking in chronic stroke survivors (van Asseldonk and Boonstra, 2016). A single session of transcranial direct current stimulation did not affect propulsion measures immediately after the intervention or at 45 min follow-up (van Asseldonk and Boonstra, 2016). In addition, results of the stimulation groups were not superior to the sham control condition (van Asseldonk and Boonstra, 2016).

4. Discussion

In the past decade, the field of stroke rehabilitation has gained an interest in interventions for improving the use of the propulsive capacity of the paretic leg. This review aimed to provide an overview of the potential effectiveness of these interventions. The included studies mostly applied exercise interventions ($N = 25$), whereas a minority of studies focused on surgical interventions (N = 2) or non-invasive brain stimulation ($N = 1$). Of the total number of 28 studies included in this review, the number of high-quality trials was limited ($N = 6$). In addition, a wide variety of propulsion measures were reported across studies, with propulsion being the primary outcome measure in eight studies (Awad et al., 2014; Betschart et al., 2018; Combs et al., 2012; Forrester et al., 2016; Hase et al., 2011; Hsiao et al., 2016; Jonsdottir et al., 2010; Kesar et al., 2015; Lauziere et al., 2014; Lewek et al., 2018; Milot et al., 2013; Palmer et al., 2017; Reisman et al., 2013). In general, mixed results were reported for interventions that evaluated propulsion measures, with some interventions yielding improvements in propulsion (Awad et al., 2014; Carda et al., 2009; Carda et al., 2010; De Luca et al., 2018; Forrester et al., 2016; Hase et al., 2011; Hsiao et al., 2016; Jonsdottir et al., 2010; Kesar et al., 2015; Lauziere et al., 2014; Lewek et al., 2018; Mirelman et al., 2010; Reisman et al., 2013; Sheffler et al., 2015), whereas others did not (Betschart et al., 2018; Bonnyaud et al., 2013a; Bonnyaud et al., 2013b; Bonnyaud et al., 2014; Combs et al., 2012; Mao et al., 2015; Milot et al., 2013; Palmer et al., 2017; Richards et al., 2004; Routson et al., 2013; Teixeira-Salmela et al., 2001; van Asseldonk and Boonstra, 2016; Yavuzer et al., 2006; Yeung et al., 2018). Similar results were found for interventions that evaluated ankle kinetics, with some interventions showing increased ankle kinetics (De Luca et al., 2018; Jonsdottir et al., 2010; Lauziere et al., 2014; Mirelman et al., 2010; Sheffler et al., 2015), whereas others did not

(Betschart et al., 2018; Carda et al., 2009; Mao et al., 2015; Milot et al., 2013; Palmer et al., 2017; Richards et al., 2004; Teixeira-Salmela et al., 2001; Yavuzer et al., 2006).

Mixed results were reported for interventions that involved gait training on a treadmill. The studies that applied regular treadmill training combined with body weight support did not yield any significant improvements in propulsion (Combs et al., 2012; Routson et al., 2013). This may be due to the body weight support reducing the limb loading and, consequently, reducing the ability to generate push-off force. In contrast, the two studies that applied a single session of treadmill training without body weight support all showed gains in propulsion (Bonnyaud et al., 2013a; Lewek et al., 2018) with the more convincing effects being demonstrated following treadmill training with an impeding force applied to the pelvis (Lewek et al., 2018). The study that applied the backward-oriented impeding force during treadmill walking, which manipulation challenges propulsion similar to walking uphill, observed these gains after only 3 min of walking in the experimental condition (Lewek et al., 2018). Apparently, the effects of this manipulation easily transfer to unrestrained treadmill walking, but the duration of the effects and the transfer to overground walking still need to be determined.

Interventions that combined gait training with functional electrical stimulation of the lower-leg muscles generally showed beneficial effects on paretic propulsion in the vast majority of the studies (Awad et al., 2014; Hsiao et al., 2016; Kesar et al., 2015; Reisman et al., 2013; Sheffler et al., 2015). These effects were observed immediately following a single training session (Kesar et al., 2015) and after a 12-week intervention (Awad et al., 2014; Hsiao et al., 2016; Reisman et al., 2013; Sheffler et al., 2015). Moreover, the improvements in paretic propulsion after the 12-week intervention were retained for at least 3 months (Awad et al., 2014; Sheffler et al., 2015). The included functional electrical stimulation interventions varied with regard to which lower-leg muscles were stimulated. The gains in paretic propulsion following gait training combined with electrical stimulation of the peroneal nerve (Sheffler et al., 2015) may be explained by the absence of any orthotics worn during training. This may have allowed participants to use their available residual ankle plantarflexion capacity, while not being hindered by an ankle-foot orthosis during push-off (Berenpas et al., 2018; Vistamehr et al., 2014). Similar beneficial effects on paretic propulsion were reported in four studies that applied stimulation of both ankle dorsal- and plantarflexion muscles, but these studies also involved gait training at faster than comfortable velocities (Awad et al., 2014; Hsiao et al., 2016; Kesar et al., 2015; Reisman et al., 2013). These studies did not separately report the effects of gait training at fast velocity alone, whereas walking at faster velocities is also known to challenge the propulsive capacity (Kesar et al., 2011). It thus remains to be determined to what extent the gains in paretic propulsion can in fact be attributed to the applied electrical stimulation or to the faster walking speed.

Interventions based on the principles of constraint-induced movement therapy (Taub, 1980) showed ambiguous effects on paretic propulsion (Bonnyaud et al., 2013b; Bonnyaud et al., 2014; Hase et al., 2011). Three weeks of treadmill training with a constraint that annihilated propulsion of the non-paretic leg yielded improvements in paretic propulsion post intervention (Hase et al., 2011), whereas two other studies that applied a single session of walking with a less severe constraint failed to demonstrate such effects (Bonnyaud et al., 2013b; Bonnyaud et al., 2014). These findings are in accordance with those from upper extremity constraint-induced movement therapy that also demonstrate the need for applying stringent constraints to the non-paretic side over a longer time period (Fleet et al., 2014). Likewise, gait training based on modified constraint-induced movement therapy may only be effective if the constraint sufficiently limits the non-paretic contribution and thus forces the paretic leg to generate greater propulsion during multiple training sessions.

Results of gait training with robotics indicate that assisted walking may be effective for promoting paretic propulsion. Gradual reduction of robotic assistance during walking improved paretic propulsion (Forrester et al., 2016; and ankle kinetics as well (De Luca et al., 2018)) during unassisted walking post intervention, with gains in propulsion being retained at six weeks follow-up (Forrester et al., 2016). In contrast, seated ankle movement training performed with the same device did not improve paretic propulsion, which observation emphasizes the relevance of task-specific training involving walking exercises (Forrester et al., 2016). Yet, another study on gait training with a robot-assisted ankle-foot orthosis that supported dorsiflexion movements during the swing phase failed to show gains in paretic propulsion (Yeung et al., 2018). It is, however, unclear from this paper whether the robotic device allowed ankle plantarflexion movements and, thus, propulsion generation during push-off. Hence, the optimal design and potential utility of robotic devices for improving paretic propulsion constitute an area for further research.

Several other studies involving exercise interventions only evaluated ankle kinetics instead of propulsion measures, and the findings should thus be interpreted with caution. Split-belt walking showed gains in ankle kinetics following a single session of walking with the paretic leg on the slow belt (Lauziere et al., 2014), but not following repeated training sessions with the leg with the longest step length on the slow belt (which was the paretic leg in eight out of the 12 participants; Betschart et al., 2018). Yet, it is interesting to note that the leg that had walked on the *fast* belt (and thus had to work harder during training) showed a significant increase in ankle plantarflexion moment at the follow-up assessment (four weeks after the end of the training; (Betschart et al., 2018)). When considering split-belt gait training as an intervention for improving propulsion, these findings raise the question whether the paretic leg should walk on the fast belt to challenge propulsion *during* the split walking condition, or on the slow belt to achieve de-adaptation *after-effects* in propulsion, which is an interesting topic for further research. Other types of exercise interventions did not yield improvements in ankle kinetics (Mao et al., 2015; Milot et al., 2013; Palmer et al., 2017; Richards et al., 2004; Teixeira-Salmela et al., 2001; Yavuzer et al., 2006), except for two exercise interventions combined with the use of (bio)feedback that showed modest effects (Jonsdottir et al., 2010; Mirelman et al., 2010). The suggested working mechanism of these interventions is based on immediate, external feedback about motor performance of the ankle joint supplementing the defective task-intrinsic feedback in patients who suffer from sensory impairments (Muratori et al., 2013). As sensory disruptions are believed to be common after stroke (Connell and Tyson, 2012), providing online external feedback on ankle movement may be a valuable adjunct to gait training interventions, but its effect on propulsion measures has yet to be determined.

As a non-exercise intervention, surgical elongation or transfer of the calf muscle-tendon complex in patients with equinovarus foot deformity showed promising results for improving paretic propulsion in a specific subgroup of stroke survivors (Carda et al., 2009; Carda et al., 2010). Before surgery, participants were not able to reach a plantigrade position of the foot with full knee extension, which severely limits locomotion. The greater ankle range of motion following surgery allows for better foot placement and weight acceptance, thereby restoring these prerequisites of walking (Carda et al., 2009; Carda et al., 2010). One year after surgery of the equinovarus foot, peak propulsive force and propulsive symmetry improved whereas, paradoxically, a decline in peak ankle moment and power were observed (Carda et al., 2009; Carda et al., 2010). These findings suggest that participants needed lower ankle moments and powers for efficiently generating propulsion. Surgical interventions may thus have the potential for improving paretic propulsion in a specific subgroup of stroke survivors with equinovarus foot deformity.

In contrast to the variable effects of interventions on propulsion outcomes and/or ankle kinetics, the vast majority of studies showed beneficial effects on walking velocity (Awad et al., 2014; Betschart et al., 2018; Bonnyaud et al., 2013a; Bonnyaud et al., 2014; Carda et al., 2009; Carda et al., 2010; Combs et al., 2012; De Luca et al., 2018; Forrester et al., 2016; Hsiao et al., 2016; Jonsdottir et al., 2010; Mao et al., 2015; Milot et al., 2013; Mirelman et al., 2010; Reisman et al., 2013; Richards et al., 2004; Routson et al., 2013; Sheffler et al., 2015; Teixeira-Salmela et al., 2001; Yeung et al., 2018). Half of the studies that demonstrated improved walking velocity did so without concurrent changes in propulsion or ankle kinetics, which suggests that the increased velocity was achieved through the development or strengthening of compensatory mechanisms to overcome deficient paretic push-off. Yet, in some studies, concurrent improvements in walking velocity and propulsion were observed, which point at the use of latent, residual propulsive capacity. The residual propulsive capacity may have become latent due to so-called ‘learned non-use’ after stroke. By reducing learned non-use, interventions may have elicited such latent propulsive capacity. Indeed, a recently published narrative review by Roelker et al. (2019) suggests that a minimal degree of ankle plantarflexion function on the paretic side may be necessary to benefit from interventions targeting paretic propulsion. Another interesting question is to what extent motor relearning may be hindered by existing compensatory mechanisms (Awad et al., 2016). Future research should therefore examine how to identify those patients who possess residual propulsive capacity and determine whether these patients are indeed likely to respond to interventions for improving paretic propulsion. The results from these future studies may provide a potential avenue for more personalized rehabilitation treatment after stroke.

This review has some limitations. First, the evidence base for propulsion interventions is limited due to a small number of randomized controlled trials, relatively low study quality, and a limited follow-up period of the included studies. Therefore, it was not possible to perform a meta-analysis. Consequently, the notion that interventions challenging and/or enabling the utilization of latent propulsive capacity of the paretic leg may improve paretic propulsion should be interpreted with caution. The same applies to the possible beneficial effects of surgical elongation or transfer of the calf muscle-tendon complex for paretic propulsion in stroke survivors with equinovarus foot deformity. Second, the wide variety of outcome measures made it difficult to compare the effectiveness of interventions. On the other hand, however, the inclusion of multiple propulsion measures made it possible to provide a comprehensive overview of the current evidence for interventions that may improve paretic propulsion. Third, the number of training sessions varied between interventions, which may have influenced the study results. Yet, no a-priori restrictions regarding the minimal number of training sessions were applied to ensure that emerging interventions for improving paretic propulsion were not missed. Fourth, the generalizability of the outcomes is limited, because most interventions were conducted in the chronic phase post stroke. The question remains whether current interventions could also be effective for improving propulsion in the subacute phase after stroke. As most rehabilitation interventions take place in the subacute phase, future research should address this issue.

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CRediT authorship contribution statement

J.F. Alingh: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Writing - original draft.**B.E. Groen:**Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Writing - original draft, Writing - review & editing.**E.H.F. Asseldonk van:**Conceptualization, Writing - review & editing.**A.C.H. Geurts:**Conceptualization, Methodology, Supervision, Writing - review & editing.**V. Weerdesteyn:**Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Writing - original draft, Writing - review & editing.

Declaration of competing interest

None of the involved authors have any conflicts of interest to report.

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