2014-04

Methodologies to assess muscle co-contraction during gait in people with neurological impairment A systematic literature review

Rosa, MCN

http://hdl.handle.net/10026.1/14265

10.1016/j.jelekin.2013.11.003
Journal of Electromyography and Kinesiology
Elsevier BV

Review

Lower limb co-contraction during walking in subjects with stroke: A systematic review

Marlene Cristina Neves Rosa [a,⇑], Alda Marques [b,1], Sara Demain [c], Cheryl D. Metcalf [c]

[a] *University of Aveiro, Department of Health Sciences (Secção Autónoma de Ciências da Saúde – SACS), University of Aveiro, Aveiro, Portugal*

[b] *University of Aveiro, School of Health Sciences, University of Aveiro, Portugal*

[c] *Faculty of Health Sciences, University of Southampton, United Kingdom*

Keywords:
Co-contraction Coactivation Gait Locomotion Walking Stroke
Cerebrovascular disease

Abstract

Purpose: The aim of this paper was to identify and synthesise existing evidence on lower limb muscle co- contraction (MCo) during walking in subjects with stroke.
Methods: An electronic literature search on Web of Science, PubMed and B-on was conducted. Studies from 1999 to 2012 which analysed lower limb MCo during walking in subjects with stroke, were included.
Results: Eight articles met the inclusion criteria: 3 studied MCo in acute stage of stroke, 3 in the chronic stage and 2 at both stages. Seven were observational and 1 had a pretest–posttest interventional design. The methodological quality was ‘‘fair to good’’ to ‘‘high’’ quality (only 1 study). Different methodologies to assess walking and quantify MCo were used. There is some controversy in MCo results, however subjects with stroke tended towards longer MCo in both lower limbs in both the acute and chronic stages, when compared with healthy controls. A higher level of post-stroke walking ability (speed; level of independence) was correlated with longer thigh MCo in the non-affected limb. One study demonstrated significant improvements in walking ability over time without significant changes in MCo patterns.
Conclusions: Subjects with stroke commonly present longer MCo during walking, probably in an attempt to improve walking ability. However, to ensure recommendations for clinical practice, further research with standardized methodologies is needed.

1. Introduction

Stroke is defined by the World Health Organization as a focal or global neurological impairment of cerebrovascular cause (Lamontagne et al., 2000; Truelsen et al., 2007). It is one of the most chronic disabling diseases (Olesen and Leonardi, 2003) and the major cause of persistent motor impairments on one side of the body, which interfere with arm function and the ability to sit up, stand and walk (Staines et al., 2009).

Walking ability is severely impaired in 25% of people with stroke (Hendricks et al., 2002; Jang, 2010), limiting functional independence and leading to reduced quality of life (Lord et al., 2004). Walking impairment may result from a combination of deficits in perception, muscle strength, sensation, muscle tone and motor control (Yavuzer, 2006; Patterson et al., 2007). A deficit in motor control is one of the most common walking deficits following stroke (Roerdink et al., 2007). Motor control is the process by which the Central Nervous System (CNS) generates purposeful and coordinated movements whilst the body interacts with the environment (Latash et al., 2010). This process depends on precisely timed and appropriately modulated synergies between muscles, including synergies between functionally opposite muscles (agonist and antagonist muscles) (Latash et al., 2010).

Muscle co-contraction is the simultaneous activity of agonist and antagonist muscles crossing the same joint (MCo) (Busse et al., 2005). When agonist/antagonist muscles work synergistically, the antagonist muscle acts as stabiliser during agonist muscle con- traction (Busse et al., 2005). This synergy is important for providing optimal joint stability, good movement accuracy and energy efficiency during functional activities, such walking (Milner, 2002; Arias et al., 2012; Knarr et al., 2012). MCo can be estimated using temporal or magnitude dimensions of electromyographic (EMG) recordings from the muscles involved (Criswell, 2007). Temporal MCo is defined as the time during which opposing muscles are simultaneously active and is usually classified using terms such normal, longer or shorter MCo duration. Magnitude of MCo is de- fined as the relative magnitude of simultaneous contraction be- tween opposing muscles (Hortobágyi et al., 2009) and is classified using terms such normal, high or reduced magnitude of MCo (Criswell, 2007).

Some differences have been found in MCo patterns between subjects with CNS disorders (Hesse et al., 2000; Lamontagne et al., 2000, 2002; Busse et al., 2005) and healthy subjects (Den Otter et al., 2004; Prosser et al., 2010) during walking. In healthy subjects, MCo is at a maximum around the knee in the loading period of gait (e.g., vastus lateralis/medial hamstrings) to provide in- creased knee stability (Fonseca et al., 2006) and around the ankle in mid-stance (e.g., tibialis anterior/soleus) to generate an efficient plantarflexor moment necessary to move the limb forward efficiently (Fonseca et al., 2006; Sasaki et al., 2009). MCo increases in healthy and impaired participants whilst learning a new skill (Vereijken et al., 1992) or in the presence of instability (Nakazawa et al., 2004). However, adverse effects of this increased MCo have been reported, such as the increase in compressive joint loading and decreased movement flexibility, resulting in decreased movement adaptability (Busse et al., 2005).

Busse et al. (2005) conducted a systematic review of MCo patterns in subjects with CNS disorders during upper and lower limb tasks, concluding that the most successful rehabilitation outputs were found in people with MCo patterns similar to those found in healthy subjects. However, only two studies included in their review assessed MCo during walking in subjects with stroke. These studies reported increases in inter-subject variability and duration and magnitude of MCo in subjects with stroke.

This research therefore systematically identified and synthesised evidence on lower limb MCo during walking in subjects with stroke.

2. Methods

2.1. Research question

The two main research questions in this study were:

1. Which MCo patterns characterise the affected and non- affected lower limbs during the acute and chronic stages of stroke recovery?
2. How do MCo patterns relate to walking ability?

2.2. Search strategy

The electronic literature search was performed in April 2013 on the following databases: Web of Science (1970-date), MEDLINE via PubMed (1948-date) and B-on Knowledge Library (1999–2013). The following search terms were applied: ‘‘co-contraction’’ OR ‘‘coactivation’’ AND ‘‘gait’’ OR ‘‘locomotion’’ OR ‘‘walking’’ AND ‘‘stroke’’ OR ‘‘cerebrovascular disease’’. The search was limited to titles and abstracts. Articles were included if they: (i) studied people with walking impairment due to stroke and (ii) analysed lower limb MCo with surface electromyography (sEMG) during walking. Articles clearly unrelated to the theme (e.g., did not include sub- jects with stroke, assessed activities other than walking), written in languages other than English or Portuguese and unpublished studies were excluded. Review papers, abstracts of communications or meetings, papers on conference proceedings, editorials, commentaries to articles and study protocols were not considered suitable for this review. Nevertheless, their reference lists, in addition to the reference lists of all included studies, were scanned to find other potentially eligible articles.

This systematic review was reported according to Preferred Reporting Items for Systematic Reviews and Meta-Analyzes (PRIS- MA) guidelines (Moher et al., 2009). The PRISMA guidelines consist of a 27-item checklist and a four-phase flow diagram to ensure the transparent and complete reporting of systematic reviews and meta-analyses (Moher et al., 2009).

2.3. Data extraction

Data from the included studies was extracted by one reviewer and then checked by a second reviewer using a data extraction table which identified: author identification, year of publication, study design, sample, walking and MCo assessment protocols, muscles assessed, main results for MCo and walking ability. Muscles assessed were reported in two different categories: muscles of the affected lower limb and muscles of the non-affected lower limb. In each sub-category, muscles were classified as thigh or shank muscles.

2.4. Quality assessment

The quality of the studies was independently assessed by two reviewers using a modified version of the scoring system developed by Hailey and co-workers (Hailey et al., 2004). This score classifies the studies on 5 levels of quality, from grade A (high quality) to E (poor quality), according to the study design and characteristics (patient selection, protocol description, statistical methods and sample size, patient disposal and outcomes re- ported) (Hailey et al., 2004). Two independent reviewers assessed the quality of the studies. Results were compared and differences were resolved by discussion.

3. Results

3.1. Study selection

Ninety-nine studies were identified: 34 duplicates were re- moved. The title and abstract of 65 articles were screened. Fifty-seven articles were excluded as they: (i) did not include subjects with stroke (n = 3), (ii) assessed activities other than walking (n = 52) and (iii) were not written in English or Portuguese (n = 2). Eight studies addressed MCo during walking in sub- jects with stroke and were included in this review (Fig. 1).

3.2. Study characteristics

From the included studies, 7 were observational assessing MCo during walking with no intervention (Lamontagne et al., 2000, 2002; Detrembleur et al., 2003; Den Otter et al., 2006, 2007; Chow et al., 2012), one of which was longitudinal (Den Otter et al., 2006), with data collected at 5 time-points. One study used a pretest–posttest design (Massaad et al., 2009), assessing walking ability before and after an intervention based on feedback about center of mass. Three studies included subjects in the acute stage of stroke (Lamontagne et al., 2000, 2002; Den Otter et al., 2006), 3 in the chronic stage (Detrembleur et al., 2003; Massaad et al., 2009; Chow et al., 2012) and 2 in both stages (Hesse et al., 1999; Den Otter et al., 2007).

In total, 142 subjects with stroke (54% male) participated in the included studies. Sample sizes varied from 6 (Massaad et al., 2009) to 30 patients with stroke (Lamontagne et al., 2000). The ages ranged from 35 (Hesse et al., 1999) to 81 (Lamontagne et al., 2000) years old. The sample in the Hesse et al. (1999) study was equally distributed in terms of the hemisphere affected (50% of right hemiparesis); was 43% right hemisphere in the Lamontagne et al. (2000); and, was not described in the other studies.

Details on the functional status of included stroke subjects are limited in the included studies. Where functional status is de- scribed a range of measures have been used, each with a different focus, raising difficulties with comparison and synthesis of findings: Fugl-Meyer Scale (FM) (Lamontagne et al., 2000, 2002), Functional Independent Measure (FIM) (Detrembleur et al., 2003), Stroke Impairment Assessment Set (SIAS) (Massaad et al., 2009) and Ashworth Scale (AS) (Detrembleur et al., 2003; Chow et al., 2012).

All except two studies (Hesse et al., 1999; Massaad et al., 2009) included a group of healthy age and gender-matched controls. Although these two studies do not contribute to our under- standing about how MCo patterns differ between healthy subjects and people post-stroke (1st review question) they are included in this review because of their analysis exploring relationships be- tween different MCo patterns and walking ability (functional parameters, e.g. energy cost, walking speed, temporal symmetry, foot contact, etc.) post-stroke (2nd review question).

Methodologies used to assess MCo during walking differed be- tween studies: 3 assessed subjects with stroke walking on the

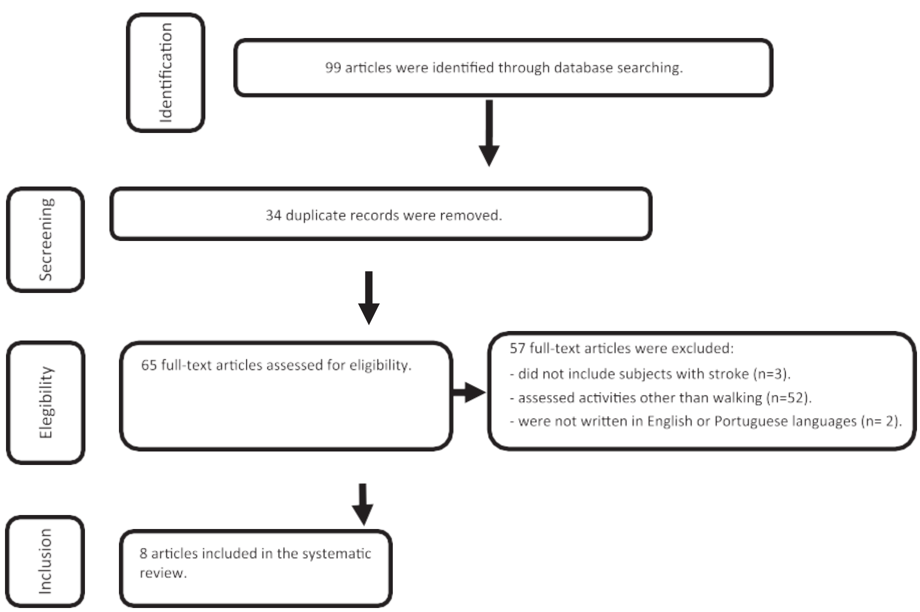


Fig. 1. Flow diagram according to the different phases of the systematic review as proposed by PRISMA.

floor (Lamontagne et al., 2000, 2002; Detrembleur et al., 2003); 3 assessed subjects whilst they were walking on a treadmill (Den Otter et al., 2006, 2007; Massaad et al., 2009) and 1 study com- pared walking on a treadmill with body-weight support and walking on the floor (Hesse et al., 1999). In most studies, subjects were instructed to walk at their normal speed (Hesse et al., 1999; Lamontagne et al., 2000, 2002; Detrembleur et al., 2003; Den Otter et al., 2007; Massaad et al., 2009; Chow et al., 2012) and in 1 study to walk at their maximum speed (Den Otter et al., 2006). Distances walked by subjects with stroke differed across the studies from 7 (Chow et al., 2012) to 10 m (Lamontagne et al., 2000, 2002; Detrembleur et al., 2003).

The MCo quantification also varied: in 1 study two raters visually inspected the graphs of an averaged and normalised sEMG signal of two antagonists muscles and classified MCo considering both temporal and magnitude of MCo (Hesse et al., 1999); 2 studies assessed the time of overlap between the linear envelopes of antagonists muscles (Lamontagne et al., 2000, 2002) and 4 studies calculated the percentage of gait cycle in which both antagonist muscles were active based on ''onset'' sEMG signal determination (Detrembleur et al., 2003; Den Otter et al., 2006, 2007; Massaad et al., 2009). Only 1 study explored the ratio between the temporal dimension and the magnitude of MCo using automatic computation methods, by implementing the following formula: the area of overlap between the linear envelopes of antagonists muscles (equivalent to MCo magnitude, divided by the overlap duration (equivalent to temporal MCo) (Chow et al., 2012).

3.3. *Quality assessment*

The Den Otter et al. study (2006) was the only one rated as A (high quality). The other 7 studies were rated as C (fair to good quality) (Hesse et al., 1999; Lamontagne et al., 2000, 2002;Detrembleur et al., 2003; Den Otter et al., 2007; Massaad et al., 2009; Chow et al., 2012).

3.4. *Synthesis of the results*

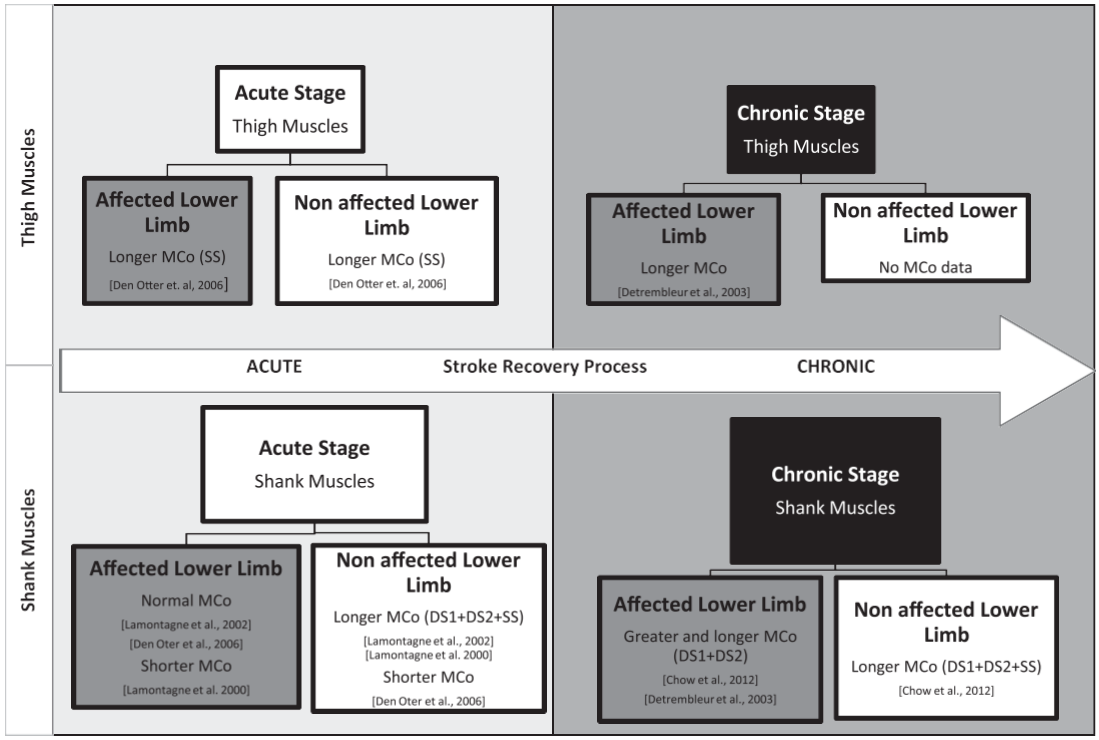
The results were organised into three main categories: (i) MCo in the affected lower limb (Fig. 2); (ii) MCo in the non-affected lower limb (Fig. 2) and (iii) MCo and walking ability after stroke. The first two categories were subdivided into shank and thigh muscles. Table 1 summarizes the data extracted from the included studies.

3.4.1. *MCo patterns in the affected lower limb*

3.4.1.1. *Shank muscles (affected limb).* A variety of MCo patterns were identified for the shank muscles of the affected lower limb in subjects with stroke (Hesse et al., 1999; Lamontagne et al., 2000, 2002; Detrembleur et al., 2003; Den Otter et al., 2006, 2007; Chow et al., 2012). In the acute stage of stroke recovery, 2 studies reported shank MCo within normal values (Lamontagne et al., 2002; Den Otter et al., 2006); however, Lamontagne et al. (2000) found that subjects with acute stroke tended to present with a shorter MCo ($p < 0.001$) between tibialis anterior (TA) and gastrocnemius (GAS) during stance phase, when compared to healthy controls.

In the chronic stage, subjects with stroke presented longer MCo between the TA and the medial gastrocnemius (GM) during the whole gait cycle (Detrembleur et al., 2003), with longer and higher values during the first ($p = 0.005$) and second double support phases ($p = 0.015$) (Chow et al., 2012).

3.4.1.2. *Thigh muscles (affected limb).* MCo values between rectus femoris (RF) and biceps femoris (BF) were longer in subjects with stroke than in healthy controls (Den Otter et al., 2007) in both acute (Den Otter et al., 2006) and chronic stages (Detrembleur et



MCo: Muscle co-contraction; DS1: affected double-support phase; DS2: non-affected double-support phase; SS: single-stance phase.

Fig. 2. Thigh and shank MCo in both affected and non-affected lower limbs and in acute and chronic stages of recovery after stroke.

Table 1
Characteristics of the studies included in the analysis of MCo during walking in subjects with stroke.

Author (year)	Design	Participants	Walking assessment protocol	Muscles	Results MCo		Walking ability
					Affected lower limb	Non affected lower limb	
Hesse et al. (1999)	Observational	$N = 18$ subjects 50% R hemiparesis 72% MCA; 28% SIH Acute and chronic stages of stroke: 2.9–11.2 months post onset 77% males 35–77 years	Treadmill (unsupported, with 15% of body weight support (BWS), with 30% of BWS) and floor walking (15 m) Mean velocity = 0.27 m/s	Shank muscles TA/GAS	Higher and longer during ground-level walking than during treadmill walking with body weight support – Gait cycle		A better initial contact (with the sole instead of the forefoot) while subjects walked in the treadmill with body weight support
Lamontagne et al. (2000)	Observational	$N = 30$ subjects 43% R hemiparesis 100% MCA FM 22 ± 6 (10–32) Acute stage of stroke: less than 6 months post onset 53% males 38–81 years $N = 17$ Healthy subjects 52% Males 43–75 years	Walk for 10 m Subjects with stroke: at natural speed Healthy subjects: walk at very slow speed	Shank muscles TA/GAS	Significantly shorter ($p < 0.01$) during single stance	Significantly longer ($p < 0.001$) during 1st and 2nd double stance longer duration ($p < 0.001$) during 1st double stance	Affected lower limb: co-contraction durations approached normal values as gait speed, postural stability and dynamic strength increased Non affected lower limb: longer co-contraction was associated with slower gait speed ($r = 0.38^{*}$)), poorer postural stability ($r = 0.51^{**}$) and lower dynamic ankle strength on the paretic side ($r = -0.37^{**}$)
Lamontagne et al. (2002)	Observational	$N = 30$ Subjects 43% R hemiparesis FM 22 ± 6 (10–32) Acute stage of stroke: less than 6 months post onset 70% Males 37–72 years $N = 15$ Healthy subjects 67% Males 43–75 years	Walk along 10 m Subjects with stroke: at natural speed Healthy subjects Natural and very slow speed	Shank muscles TA/GAS	Within normal values in SW phase + stance phase Significant difference between both legs in 1st double stance + single stance	Longer co-contraction, than controls walking at natural speed ($p < 0.05$) and at very slow speed ($p < 0.01$) during – 1st double stance and single stance	Reduced plantarflexor moment on the affected lower limb was combined with excessive antagonist co-contraction at the ankle on the non-affected lower limb
Detrembleur et al. (2003)	Observational	$N = 9$ subjects 67% R hemiparesis FIM 123 (118–125) SIAS (44–68) AS (0–3) Chronic stage of stroke: 6–85 months post onset 55% males 37–77 years	Walk across 10 m at a comfortable speed and at fast speed	Thigh muscles RF/BF Shank muscles TA/LG	Around 10% and 1.5–6 times longer than normal during all Gait cycle Around 40% and 1.5–6 longer than normal during all Gait cycle		Increase in muscle co-contraction was combined with an increase in energy cost of walking (energy expenditure/speed of walking), proportional to the increase in the total mechanical work (work done by muscles), but with normal work production efficiency (mechanical work/energy expended) Hypothesis to explain normal work production efficiency Unaffected lower limb performed most of the work

(*continued on next page*)

Table 1 (*continued*)

Author (year)	Design	Participants	Walking assessment protocol	Muscles	Results MCo		Walking ability
					Affected lower limb	Non affected lower limb	
Den Otter et al. (2006)	Observational	$N = 14$ subjects 35.7% R hemiparesis 42.8% Impaired SS 78.57% Impaired TC Acute stage of stroke: 23–52 days post onset 43% males 39–71 years $N = 14$ Healthy subjects 43% males 42.8y ± 12.3 years	Walking on a treadmill: as early as possible after admission; 1, 3, 6 and 10 weeks after baseline Tested a maximum speed (maintained during 40 s); speed was increased as much as possible	Thigh muscles BF/RF Shank muscles TA/GM	Longer ($p < 0.05$) in single stance at baseline; no significant change during follow up Stroke:63 ± 34% healthy:31 ± 21% Non-statistically different from controls during all Gait cycle at baseline; no significant differences during follow ups	Longer ($p > 0.05$) in single stance, compared to controls during all Gait cycle at baseline; no significant change during follow up Shorter duration ($P > 0.05$) during all Gait cycle at baseline; no significant differences during follow ups	No changes in temporal asymmetry walking speed increased over time General mobility (rivermead mobility index) of subjects increased over time subjects ambulatory independence (functional ambulation categories) increased over time
Den Otter et al. (2007)	Observational	$N = 24$ subjects 58% R hemiparesis 37.5% Impaired SS 67% Impaired TC Acute and chronic stages: 3–21 months after stroke 42% Males 58.58 ± 13.17 years $N = 14$ Healthy subjects 43% Male 42.85 ± 12.3 years	Walking on a treadmill for 40 s Tests with a self-selected speed	Thigh muscles BF/RF Shank muscles TA/GAS	Exceed controls levels in affected double support phase; ($p < 0.05$) Stroke: 61% ± 31 No significant differences, compared with controls	Exceed controls levels; all gait cycle; ($p < 0.05$) Stroke: 62% ± 31 No significant differences, compared with controls	
Massaad et al. (2009)	Pretest–Posttest	$N = 6$ subjects 67% R hemiparesis SIAS (47–67) Chronic stage of stroke: 48–285 months post onset 67% males 47 ± 13 years	18 training sessions –30 min walking in a treadmill with feedback of the CM displacement (3 trials, 10 min each) Walking at comfortable speed; – walking period increased 5 min every 2 weeks	Thigh muscles VL/BF Shank muscles TA/GM	Decreased significantly (10%; $p = 0.026$) during all Gait cycle pre: 44% ± 9 post: 39% ± 13 Did not change significantly ($p = 0.516$) during all Gait cycle Pre: 21% ± 16 Post: 18% ± 17	Decreased significantly by 15% ($p = 0.012$) during all Gait cycle Pre:40% ± 7 Post: 34% ± 10 Did not change significantly ($p = 0.249$) during all Gait cycle pre 27:% ± 21 Post: 21% ± 9	Vertical CM displacement decreased Gait energy cost decreased
Chow et al. (2012)	Observational	$N = 11$ Subjects AS 2 ± 0.2 Chronic stage of stroke: 45 ±46 months post onset 27% Males 41 ±9 years $N = 11$ Healthy subjects Gender and age matched	Walking 7 m (8–10 times) Stroke subjects at a self-selected speed Healthy subjects at a self-selected very slow speed	Shank muscles TA/GM	Greater ($p = 0.001$) during 2nd double stance Greater ($p = 0.015$) during 1st double stance Greater ($p = 0.005$) during 1st double stance + single stance	Greater compared to controls ($p = 0.038$) during 1st double stance	

EMG: electromyography, %: percentage, TA: tibialis anterior, GAS: gastrocnemius, GM: medial gastrocnemius; LG: lateral gastrocnemius; VL: vastus lateralis; BF: biceps femoris, RF: rectus femoris; MCA, middle cerebral artery; SIH, supra intracranial hemorrhage; R, right; FM, Fugl-Meyer scale; FIM, Functional Independence Measurement; SIAS, Stroke Impairment Assessment Set; AS, Ashworth Scale; SS, Sensibility Score; TC, Trunk Control.

* Statistically significant at $p < 0.05$.

** Statistically significant at $p < 0.001$.

al., 2003). This finding was statistically significant during single stance (63%; $p < 0.05$) in the acute stage (Den Otter et al., 2006).

3.4.2. MCo patterns in the non-affected lower limb

3.4.2.1. Shank muscles (non-affected limb). Contradictory findings were found for MCo of the shank in the non-affected lower limb.

Two studies identified statistically significant longer shank (TA/GAS) MCo (Lamontagne et al., 2000, 2002) in subjects in the acute stage of stroke when compared to healthy controls, specifically during the first and second double support phases ($p < 0.001$) (Lamontagne et al., 2000) and during the entire stance phase ($p < 0.05$) (Lamontagne et al., 2002). However, Den Otter et al. (2006), identified non-statistically significant shorter shank (TA/GM) MCo during the whole gait cycle, in subjects in the acute stage compared to healthy controls.

One article reported shank MCo in the chronic stage (Chow et al., 2012) and concluded that the non-affected lower limb presented with a greater MCo (considering both magnitude and temporal domain) (Chow et al., 2012) during the first double support phase, when compared to healthy subjects ($p = 0.038$).

3.4.2.2. Thigh muscles (non-affected limb). Thigh MCo between vastus lateralis (VL) and BF of the non-affected lower limb was only assessed in the acute stage by Den Otter et al. (2006). These authors found a significantly longer thigh MCo during single stance phase (61%; $p < 0.05$) in subjects with stroke than in healthy sub- jects. No data were available for the chronic stage of the disease.

3.4.3. MCo and walking ability after stroke (both limbs)

In the included studies, the relationship between MCo and several walking outcomes was assessed: initial contact pattern (Hesse et al., 1999), energy cost (Detrembleur et al., 2003; Massaad et al., 2009), total mechanical work (Detrembleur et al., 2003), mobility index, functional ambulation classification (Den Otter et al., 2006), walking speed (Lamontagne et al., 2000; Den Otter et al., 2006), temporal asymmetry (Den Otter et al., 2006), ankle strength, postural stability (Lamontagne et al., 2000), plantarflexor and dorsiflexor moments (Lamontagne et al., 2002) and center of mass dis- placement (Massaad et al., 2009).

Relationships between these variables and MCo in both the affected and non-affected lower limbs were found. In the affected lower limb, longer shank and thigh MCo was associated with increased mechanical work (the work performed by muscles) and energy costs (energy expenditure/walking speed). However, no relationship with work production efficiency (mechanical work/energy expenditure) was observed (Detrembleur et al., 2003). Normal values of shank MCo were related to a normal foot position at initial contact (Hesse et al., 1999) and to a higher dynamic ankle strength, estimated from the peak plantarflexor moment of force during a gait cycle (Lamontagne et al., 2000). In the study of Massaad et al. (2009), both energy cost and MCo of thigh muscles in both affected and non-affected lower limbs were decreased after an intervention using center of mass feedback. In the non-affected lower limb, significantly longer thigh MCo was associated with an improvement in walking speed and higher level of walking independence (Den Otter et al., 2006). An increase in shank MCo of the non-affected lower limb was associated with reduced motor ability of the affected lower limb in terms of the plantarflexor moment (Lamontagne et al., 2002), dynamic ankle strength and postural stability (Lamontagne et al., 2000). Subjects with stroke presenting with measures of postural stability, dynamic ankle strength (Lamontagne et al., 2000) and temporal asymmetry (Den Otter et al., 2006) close to normal ranges were those with normal shank MCo in the affected lower limb.

In the study of Den Otter et al. (2006), subjects with stroke were followed for 10 weeks after walking acquisition and showed a significant improvement in walking speed, general mobility and ambulatory independence. However, these improvements were not associated with significant changes in temporal MCo of thigh or shank muscles which remained longer throughout the 10 weeks. This study therefore observed that walking recovery was not associated with duration of MCo.

4. Discussion

This systematic review identified and synthesised the existing evidence on lower limb MCo during walking in subjects with stroke. Only 8 studies were included, and these used a range of different methods, restricting comparison of the results across studies and the degree of confidence in the evidence. Nevertheless, this systematic review did enable us to identify some specific trends in the available MCo data and to explore MCo contribution to the recovery of walking ability post-stroke as outlined below.

4.1. MCo in the affected lower limb

Only three studies have explored thigh MCo (Detrembleur et al., 2003; Den Otter et al., 2006, 2007) and six have explored shank MCo (Lamontagne et al., 2000, 2002; Detrembleur et al., 2003; Den Otter et al., 2006, 2007; Chow et al., 2012). Despite this limited evidence, results suggest specific trends for MCo patterns of subjects with stroke.

Longer thigh MCo was observed for single leg stance in the acute stage (Den Otter et al., 2006). It is known that the greatest difficulties in the acute stage are experienced during stance, in particular in controlling knee position during loading (Werner et al., 2002). Longer thigh MCo might, therefore, be an important adaptation strategy in the early days after stroke.

Longer shank MCo in the chronic stage during double support phase (Chow et al., 2012), suggests that these muscles may also play an important adaptation role later in stroke recovery (Det- rembleur et al., 2003; Massaad et al., 2009; Chow et al., 2012).Walking places different functional demands dependent on the stage of recovery. For instance acute patients rarely walk out- side the home, but as recovery occurs, people often commence community walking and thus face increasing demands due to the variability and uncertainty of the environment. Consequently different MCo strategies may be required and developed to adapt not only to the differing abilities but also the varying environments. During the acute stage, people with stroke present significant weakness in the dorsiflexors (Olney and Richards, 1996), limiting the ability of these muscles to contribute to walking stability through MCo. Dorsiflexor strength increases with recovery, enabling the necessary ankle stability required to walk in community environments which may explain the finding of increased MCo in the chronic stage. These findings support the idea that MCo after stroke may represent an important adaptation strategy to enhance a safer gait, producing different patterns according to different stages of stroke recovery (Paul Cordo et al., 1997).

4.2. MCo in the non-affected lower limb

Few studies have explored thigh MCo in the non-affected lower limb in the acute stage (Den Otter et al., 2006, 2007) and none in the chronic stage. The longer thigh MCo observed during stance can probably be attributed to the need for greater stability (Raja et al., 2012) required to sustain the prolonged stance phase commonly seen on the non-affected lower limb. This prolonged stance is often a motor adaptation for the limited efficiency of the affected lower limb to support body weight (Olney and Richards, 1996). In general, MCo of the non-affected lower limb can be an important strategy developed to adapt the walking pattern to physical impairments in the affected side and therefore, might play an important role in the walking efficiency post-stroke (Buurke et al., 2008).

Three studies assessing shank MCo of the non-affected lower limb in the acute stage of recovery produced contradictory results (Lamontagne et al., 2000, 2002; Den Otter et al., 2006) and only one study explored these muscles in the chronic stage (Chow et al., 2012). Some trends can be observed in acute and chronic stages: longer thigh MCo was identified in single stance phase in the acute stage (Den Otter et al., 2006) and longer shank MCo was identified for double support phases in both acute (Lamontagne et al., 2000, 2002) and chronic stages (Detrembleur et al., 2003; Chow et al., 2012).

During the double support phase, longer shank MCo might be an adaptation strategy for disturbed inter-limb coordination and lack of efficiency in weight transference from one lower limb to an- other (Geurtsa et al., 2005). Olney and Richards (1996) argued that efficiency in weight transference depends on good medio-lateral control, obtained through a strong ankle plantarflexor moment at push-off of the unloading limb. In this way, longer shank MCo during push-off from the non-affected lower limb may help generate a stronger ankle plantarflexor moment necessary to move this limb forward quickly and efficiently thus reducing the duration of loading on the affected leg.

Overall, the findings of this review suggest increased duration of MCo during walking after stroke in both the affected and non- affected limb, most likely as an adaptation strategy to increase walking stability. In particular, different patterns were seen for different walking phases and different muscle groups. This may be indicative of recovery mechanisms, an artifact of the various methods employed in the studies (e.g. different walking speeds and surfaces) (Gross et al., 2013) or of confounding factors not carefully addressed in the analysis and interpretation (Zhang et al., 1997). For instance, walking post-stroke is characterised by significantly slower speeds and high inter-subject variability which will affect stride parameters and consequently MCo patterns (Peterson and Martin, 2010; Gross et al., 2013). Slowest walking speeds post-stroke are usually associated with inability to recruit additional MCo (Gross et al., 2013). MCo patterns seen in subjects with stroke may therefore be an artifact more reflective of gait speed than any other underlying stroke related impairment. Therefore, methodologies of analysis that control for the effect of walking speed are needed to clarify the single contribution of MCo to walking function. Variations in joint position also impact on muscle length and consequently influence MCo (Zhang et al., 1997). Considering the high variability in walking patterns and therefore joint positions during post-stroke gait, (Quervain et al., 1996), this presents a further confounding factor which needs to be considered and/or controlled in future studies.

4.3. MCo and walking ability after stroke

The studies in this review identified several relationships between walking ability parameters and MCo. Subjects with stroke with MCo values within normal ranges in the affected lower limb tended to exhibit greater walking performance, characterised by more efficient kinematics patterns (Hesse et al., 1999) and higher dynamic strength (Lamontagne et al., 2000). The opposite tends to be observed in the non-affected lower limb: walking speed and level of walking independence were greater in subjects with thigh MCo above normal when compared to healthy individuals (Den Otter et al., 2006). Findings from the included studies suggest strong relationships between MCo and kinematics, dynamic strength, postural stability, walking speed and walking independence in subjects with stroke. Similar relationships have been reported in osteoarthritis (Heiden et al., 2009), cerebral palsy (Poon and Hui-Chan, 2009) and Parkinson's disease (Ramsey et al., 2004) and in healthy elderly people (Melzer et al., 2004).

In addition, longer MCo was reported as being related to in- creased energy costs of walking. This is in accordance with previous literature identifying MCo as a costly metabolic process (Missenard et al., 2008). Despite this, Detrembleur et al. (2003) argued that increased MCo in the non-affected lower limb helps establish a well-balanced efficiency in walking. By increasing MCo, the non-affected lower limb increases its mechanical work and replaces some of the work that cannot be performed by the affected lower limb. Therefore, despite MCo being an energy consuming process, it may help restoring walking efficiency (Detrembleur et al., 2003).

Only one longitudinal study explored the relationship between changes in MCo and changes in walking ability (Den Otter et al., 2006). In this study, subjects with stroke were followed over 10 weeks and a significant improvement in walking ability reported with no significant changes in temporal MCo. This finding contradicts the associations seen in the observational studies. However, in the analysis of these results several limitations must be considered. In this study, walking was assessed on a treadmill at maximum walking speed (which differs from the gait protocol in the other studies) and may not reflect the natural functional demands which subject's experience. Therefore, during this walking assessment, subjects might have exhibited different adaptation strategies from those developed in daily living conditions (Hesse et al., 1999). Hence, this is an important methodological limitation. Moreover, only temporal MCo was assessed and its magnitude ignored. However, for MCo assessment both temporal and magnitude dimensions should be considered as both are important aspects of motor control (Fonseca et al., 2001).

4.4. Limitations and recommendations for future research

This review identified some trends in MCo patterns during walking post-stroke and has found relationships between these patterns and walking ability parameters. However, given the limited number of studies that have been conducted in this field and their methodological limitations some inconsistent findings were presented. These methodological limitations include small sample sizes and lack of standardisation in: walking assessment protocols, the methods for measuring and analysing MCo and the walking ability outcome measures selected. Moreover, data on mean MCo and respective measures of variation were not reported in all studies, instead only levels of significance were provided. This lack of quantitative MCo data made comparison of results across studies difficult. Given the small number of studies and the diversity of methods more research, with standardised designs, is needed to further our understanding of MCo patterns during walking after stroke. In particular, longitudinal studies exploring changes in MCo over time and the relationship of these to improvements in walking ability parameters are urgently required.

4.5. Development and validation of methods for MCo assessment during walking in subjects with stroke

Application of the ICF core set for stroke to characterise the subjects' general functionality would facilitate the agreement of functional outcomes across studies, providing further under- standing of relationships between MCo patterns and subjects' clinical and functional status.
Standardisation of walking protocols (surface, speed, distance) for MCo assessment purposes would reduce confounding MCo factors when comparing results across studies.

- Adherence to guidelines for sEMG acquisition and analysis would avoid significant differences in the muscle activity measurement across studies.
- Establishment of an expert working group to generate recommendations about the most appropriate formulas/computational approaches for MCo quantification in subjects with stroke would facilitate comparison of MCo across studies.

5. Conclusions

In this review, subjects with stroke tended to exhibit longer MCo during walking than healthy controls, however MCo patterns appeared to vary depending on the stage of stroke recovery. MCo strategies during walking may change to adapt the walking pattern to the different functional demands specific to acute or chronic stages. These strategies may be developed in both the affected and non-affected lower limbs, with MCo patterns in the non- affected lower limb helping to establish normal walking efficiency. Establishing consensus, using robust study designs, is important for enhancing the design of interventions for walking recovery.

Conflict of Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgements

This work was funded by a PhD Grant from Fundação para a Ciência e Tecnologia (FCT), Portugal (Ref. SFRH/BD/74927/2010).

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Marlene Rosa received her Degree of Physiotherapy in 2001 from School of Health Sciences in University of Aveiro. She completed her Masters in Motor Development at Sports Faculty in University of Porto. In her Master thesis it was explored the motor control during the recovery of the hemiparetic upper limb post-stroke. She has currently a PhD grant funded by Fundação para a Ciência e Tecnologia (FCT) – Portugal, working in the Department of Health Sciences (Secção Autónoma de Ciências da Saúde – SACS), at University of Aveiro and focusing her research interests in the study of muscle co-contraction during walking post-stroke.

Alda Marques graduated in physiotherapy at *Escola Superior de Tecnologias da Saúde de Coimbra*, Portugal (1999). Her Master degree was obtained in Biokinetics of the development at Faculdade de Ciências do Desporto e Educação Física da Universidade de Coimbra, Portugal (2003). Marques obtained her PhD degree in 2008 funded by Fundação para a Ciência e Tecnologia (FCT), Portugal, working on a joint project between the School of Health Sciences, Faculty of Medicine, Health and Life Sciences and the Institute of Sound and Vibration Research, University of Southampton, United Kingdom. Since 2009, Marques has been principal investigator of several funded research projects on respiratory sounds, respiratory rehabilitation and dementia. She has also lead an integrated action and has been a researcher of other research projects. Her current research focus explores the development and implementation of new measures and healthcare technologies to be use in rehabilitation interventions (e.g., respiratory acoustics as a diagnostic and monitoring measure), and designing innovative rehabilitation programs for people with chronic diseases (e.g., Stroke, COPD, Chronic Kidney Failure). Marques is author of several international publications and is currently a senior lecturer and a researcher at Escola Superior de Saúde (School of Health Sciences), University of Aveiro, Portugal.

Sara Demain qualified as a physiotherapist in 1990. She worked in NHS hospitals in the Midlands, specialising in neurological rehabilitation. Sara completed an MSc in Rehabilitation before becoming a Lecturer in Physiotherapy at the University of Southampton, where she teaches neurology and research methods. All of Sara's research focuses on the psychosocial processes affecting neurological rehabilitation; for instance Sara's PhD explored the process of discharge from physiotherapy following stroke. Sara has recently been awarded an NIHR post-doctoral fellowship to explore the burdens generated by stroke rehabilitation.

Dr. **Cheryl D. Metcalf** completed a prestigious Research Council's (U.K.) Roberts Fellowship in Life Sciences Interface at the University of Southampton, Southampton, U.K and is currently a Lecturer in Biomechanics in the Faculty of Health Sciences, University of Southampton. Her research interests include the hand and wrist biomechanics in unimpaired, neurological and musculoskeletal impairment, kinematic assessment of complex skill acquisition, developing and assessing health technology for home-based evaluation and assessment. She is particularly interested in technologies that measure movement and function, and developing novel methods of capturing this information.