Title: "Methodologies to assess muscle co-contraction during gait in people with neurological impairment - a systematic literature review."

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ABSTRACT

Purpose: To review the methodologies used to assess muscle co-contraction (MCo) with surface electromyography (sEMG) during gait in people with neurological impairment.

Methods: The Scopus (1995-2013), Web of Science (1970-2013), PubMed (1948-2013) and B-on (1999-2013) databases were searched. Articles were included when sEMG was used to assess MCo during gait in people with impairment due to central nervous system disorders (CNS).

Results: Nineteen articles met the inclusion criteria and most studied people with cerebral palsy and stroke. No consensus was identified for gait assessment protocols (surfaces, speed, distance), sEMG acquisition (electrodes position), analysis of sEMG data (filters, normalisation techniques) and quantification of MCo (agonist-antagonist linear envelopes overlapping or agonist-antagonist overlapping periods of muscles activity, onset delimited).

Conclusion: Given the wide range of methodologies employed, it is not possible to recommend the most appropriate for assessing MCo. Researchers should adopt recognized standards in future work. This is needed before consensus about the role that MCo plays in gait impairment in neurological diseases and its potential as a target for gait rehabilitation can be determined.

1. Introduction

Gait patterns are usually impaired in people with dysfunction of the Central Nervous System (CNS), such as stroke (Knutsson et al. 1979), traumatic brain injury (Chow et al. 2012), cerebral palsy (Hesse et al. 2000) or Parkinson´s disease (Dietz et al. 1981). Walking is a very complex function involving multiple interactions between muscle groups which can be adapted to enable walking at different speeds or on different surfaces (Winter 2009.). Neurological impairments can generate many deviations in muscle activity and gait kinematics from those seen in healthy individuals and reduce the ability to adapt gait appropriately to different environmental conditions. Gait patterns in people with neurological impairment have been characterized by abnormal muscle co-contraction, especially when postural stability is challenged (Lamontagne et al. 2000).

Muscle Co-contraction (MCo) is the mechanism that regulates simultaneous activity of agonist and antagonist muscles crossing the same joint (Busse et al. 2005). There is no consensus about the role that MCo plays in the various stages of recovery after CNS disease. However as MCo has been demonstrated to be important for providing adequate joint stability, movement accuracy and energy efficiency (Higginson et al. 2006) and adapting to environmental demands (Darainy et al. 2008), its importance in neurological recovery is worthy of consideration.

Accurate determination of the impact of neurological impairment on MCo during gait requires robust measurement techniques which take careful consideration of the environmental conditions under which gait is assessed (Den Otter et al. 2004). For instance, walking on a ground surface instead of on a treadmill, walking at different speeds and for longer distances/duration would increase MCo recruitment and the variability between subjects (Parvataneni et al. 2009; Knarr et al. 2012). The first research question addressed by this review therefore is:

What are the main characteristics of the gait assessment protocols particularly, the surfaces where people walked, the speed, distance and time spent walking? Which muscles have been assessed?

All measurement techniques, including sEMG, are liable to measurement error which can reduce validity and reliability and confound interpretation of the findings. MCo assessment during functional movements, such as walking, requires the analysis of the relative variations in agonist and antagonist contraction over time using surface electromyography (sEMG) equipment (Fonseca et al. 2001; Fonseca et al. 2004). Standards have been developed for reporting sEMG signals in different processing stages, such as the signal acquisition (Surface Electromyography for the Non-Invasive Assessment Muscles (SENIAM) guidelines), and analogue and digital analysis (International Society of Electrophysiology and Kinesiology (ISEK) guidelines) (Merletti 1999), but the implementation of these is variable. Despite these guidelines, controversies remain about the most appropriate techniques of sEMG signal analysis; (e.g., selection of normalisation technique) leading to inconsistencies across studies (Burden et al. 2003). Therefore, the second research question this review sought to answer is:

What are the main steps in the acquisition and analysis of the sEMG signals and which parameters have been considered when quantifying MCo?

A single definition of MCo would also be facilitate interpretation of MCo outcomes during walking. However MCo has been defined in different ways: the magnitude; the time; or a ratio between the magnitude and time of simultaneous activation of opposite muscles (Fonseca et al. 2001). As a result of different definitions, different formulas or computational approaches to quantify MCo have been employed (Fonseca et al. 2001). All these methodological differences limit the comparison of data across studies and the understanding of the mechanisms of MCo. The third research question for this review is therefore:

Which formulas or computational approaches have been used to quantify MCo?

This paper addresses the need to systematically review, synthesize and critique the methodologies used in this field, contributing to a better understanding of the mechanisms underpinning MCo and of its role in gait in people with CNS disease.

2. Methods

2.1. Variable of interest

The variable of interest in this study was MCo during gait, presented as the time and/or the magnitude of simultaneous contraction between opposite muscles (Fonseca et al. 2001).

2.2. Search strategy

The literature search was performed from date of inception until end of November 2012 on the following databases: Scopus (1995-2013), Web of Science (1970-2013), PubMed (1948-2013) and B-on (1999-2013). B-on includes the Academic Search Complete (EBSCO), Annual Reviews, Elsevier-Science Direct, Nature, Springer Link (Springer/Kluwer), Taylor &Francis and Wiley Online Library (Wiley). Weekly updates were performed until October 2013.

The following search term (free text words) combinations were used in Pubmed database: co-contraction AND gait, co-contraction AND locomotion, co-contraction AND Walking; co-activation AND gait; co-activation AND locomotion, co-activation AND walking. Search strategies in the other databases were derived from Pubmed. The search terms were limited to titles and abstracts. The reference lists of all studies were also scanned to identify other potentially eligible articles.

The study was conducted using the systematic review method proposed by the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Moher et al. 2009), as shown in Figure 1.

Full papers, written in English or Portuguese that met the following criteria were included if they: (i) studied gait impairment due to neurological diseases, such as stroke, Parkinson´s disease, cerebral palsy, traumatic brain injury and other CNS dysfunctions; and ii) analysed MCo during gait of the lower or upper limb or trunk using sEMG. All articles were independently reviewed by two reviewers for relevance and quality using PRISMA (Moher et al. 2009). Any discrepancies were resolved through discussion.

3. Results

Figure 1 portrays the number of articles identified, the numbers and reasons for exclusion and the total number of studies included in the final review A descriptive analysis of the methodologies (study

design; sample; data collection protocol; sEMG data acquisition and analysis and quantification of MCo) of the included studies is presented in Table 1.

Figure 1: Flow-chart according to the different phases of the systematic review as proposed by PRISMA

3.1. Study design and sample

Most studies included in this review had observational designs, with the exception of two experimental studies (Hesse et al. 2000; Massaad et al. 2010). The observational studies assessed MCo during gait with no intervention or program. From those studies, only one was longitudinal (Den Otter et al. 2006), with data collection over five time points. The experimental study used non-randomized control groups and assessed gait before and after an intervention (Concato 2004). With the exception of six articles (Hesse et al. 1999; Damiano et al. 2000; Hesse et al. 2000; Detrembleur et al. 2003; Keefer et al. 2004; Massaad et al. 2010) all others included a group of healthy participants to provide normative comparison of MCo. MCo during gait was studied in several neurological conditions including stroke (Knutsson et al. 1979; Hesse et al. 1999; Lamontagne et al. 2000; Lamontagne et al. 2002; Detrembleur et al. 2003; Den Otter et al. 2006; Den Otter et al. 2007; Massaad et al. 2010; Chow et al. 2012), cerebral palsy (Leonard et al. 1991; Unithan et al. 1996; Damiano et al. 2000; Hesse et al. 2000; Keefer et al. 2004; Wakeling et al. 2007; Prosser et al. 2010; Assumpção et al. 2011), multiple sclerosis and cerebral tumor (Knutsson et al. 1979; Dietz et al. 1981), Parkinson's disease (Dietz et al. 1981; Arias et al. 2012), traumatic brain injury (TBI) (Chow et al. 2012) and finally, myelopathy, sclerosis, amyotrophy and meningitis (Dietz et al. 1981).

Sample sizes varied from 5 (Leonard et al. 1991) to 30 participants (Lamontagne et al. 2000). In some studies, age (Knutsson et al. 1979; Dietz et al. 1981; Den Otter et al. 2006; Den Otter et al. 2007; Prosser et al. 2010) and gender (Knutsson et al. 1979; Lamontagne et al. 2000; Lamontagne et al. 2002; Prosser et al. 2010) criteria were not well-matched between the group of people with CNS disorders and the healthy controls. Anthropometric data, including height and weight, were described in seven studies (Unithan et al. 1996; Damiano et al. 2000; Lamontagne et al. 2000; Lamontagne et al. 2002; Detrembleur et al. 2003; Prosser et al. 2010; Assumpção et al. 2011). The others described either weight (Hesse et al. 2000) or height (Massaad et al. 2010; Arias et al. 2012).

3.2. Research Question 1: What are the main characteristics of the gait assessment protocols particularly, the surfaces where people walked, the speed, distance and time spent walking? Which muscles were assessed?

Different surfaces were used to assess gait in the included studies. In some studies, a walkway (usually a corridor on the floor) was used (Knutsson et al. 1979; Damiano et al. 2000; Hesse et al. 2000; Lamontagne et al. 2000; Lamontagne et al. 2002; Detrembleur et al. 2003; Keefer et al. 2004; Wakeling et al. 2007; Assumpção et al. 2011; Arias et al. 2012; Chow et al. 2012), whereas in others participants walked on a treadmill (Dietz et al. 1981; Leonard et al. 1991; Unithan et al. 1996; Den Otter et al. 2006; Den Otter et al. 2007; Massaad et al. 2010; Prosser et al. 2010). Gait performance on a treadmill was compared to gait performance on the ground in one study (Hesse et al. 1999).

A wide variety of instructions were given to participants regarding the speed they should walk. A number of studies used a free/normal/self-selected speed (Knutsson et al. 1979; Dietz et al. 1981; Leonard et al. 1991; Hesse et al. 1999; Damiano et al. 2000; Hesse et al. 2000; Lamontagne et al. 2000; Lamontagne et al. 2002; Detrembleur et al. 2003; Den Otter et al. 2007; Wakeling et al. 2007; Massaad et al. 2010; Prosser et al. 2010; Assumpção et al. 2011; Chow et al. 2012). In three studies subjects were instructed to walk as quickly as possible (Unithan et al. 1996; Hesse et al. 1999; Den Otter et al. 2006) but only in two of these studies, average gait speeds were reported: 0.27 meters per second (Hesse et al. 1999); an average of 3 kilometers per hour achieved when asking patients to walk at 90% of maximum speed during 2 minutes(Unithan et al. 1996). Keefer et al. (Keefer et al. 2004) asked patients to perform three 5-minute walking trials at 0.67, 0.89 and 1.12 meters per second, controlled by a treadmill setting. One study (Arias et al. 2012) assessed walking in three different conditions: subjects were first instructed to walk at their preferred speed, then at fast speed and finally, to match their steps with a pulsing rhythm provided by a metronome (Arias et al. 2012). Moreover, in most studies (Knutsson et al. 1979; Dietz et al. 1981; Leonard et al. 1991; Hesse et al. 1999; Damiano et al. 2000; Hesse et al. 2000; Lamontagne et al. 2000; Lamontagne et al. 2002; Detrembleur et al. 2003; Wakeling et al. 2007; Massaad et al. 2010; Prosser et al. 2010; Assumpção et al. 2011; Arias et al. 2012; Chow et al. 2012) impaired and healthy participants were given the same

instructions but in 3 other studies (Lamontagne et al. 2000; Lamontagne et al. 2002; Chow et al. 2012) the healthy participants were asked to walk "very slowly" in an attempt to control for the effect of gait speed on MCo patterns.

The walking distance or the time spent walking also varied: four studies (Lamontagne et al. 2000; Hesse et al. 2001; Lamontagne et al. 2002; Detrembleur et al. 2003) asked participants to walk 10 meters and Knutsson et al.(Knutsson et al. 1979) and Chow et al. (Chow et al. 2012) used 5 meters. Distances longer than 10 meters were also used by Hesse et al. (Hesse et al. 1999), Damiano et al. (Damiano et al. 2000) and Arias et al. (Arias et al. 2012); whilst the time spent walking was the criterion used to define the protocol in the other studies, ranging from 40 seconds (at a maximum speed) (Keefer et al. 2004) to 30 minutes (at a comfortable speed) (Massaad et al. 2010).

MCo was acquired from different muscles during gait performance. Four studies assessed thigh muscles (Damiano et al. 2000; Keefer et al. 2004; Prosser et al. 2010; Assumpção et al. 2011), five studies assessed only shank muscles (Dietz et al. 1981; Lamontagne et al. 2000; Lamontagne et al. 2002; Arias et al. 2012; Chow et al. 2012) whilst the others assessed muscles of the entire lower limb. Only one study assessed MCo from trunk muscles and (Prosser et al. 2010) there were no articles assessing MCo of the upper limb or any other body structures during gait.

3.3. Research Question 2: What were the main steps in the acquisition and analysis of the sEMG signals and which parameters were considered when quantifying MCo?

Data acquisition was inconsistent across studies. Only five studies followed the SENIAM recommendations for both electrode placement and skin preparation (Detrembleur et al. 2003; Den Otter et al. 2006; Den Otter et al. 2007; Prosser et al. 2010; Assumpção et al. 2011). Six studies did not describe electrode position (Dietz et al. 1981; Leonard et al. 1991; Damiano et al. 2000; Hesse et al. 2000; Wakeling et al. 2007; Massaad et al. 2010); only one of these described how the skin was prepared (Damiano et al. 2000).

The analogue and digital processing of the sEMG signal was performed differently across studies. Analogue processing usually involves two main steps: pre-amplification and application of filters.

However, two older studies (Knutsson et al. 1979; Dietz et al. 1981) included in this review, used analogue techniques to construct the linear envelope (LE) of the signal.

Several amplifiers were employed, with different values of common mode rejection ratio and input impedance, assuming values from 50dB (Chow et al. 2012) to 110dB (Assumpção et al. 2011) and values from 10KΩ (Unithan et al. 1996; Lamontagne et al. 2000; Lamontagne et al. 2002) to 31MΩ (Chow et al. 2012) respectively.

Analogue filter characteristics were also different, assuming high-pass cut-off values of 10 Hz (Unithan et al. 1996), 20Hz (Lamontagne et al. 2000; Lamontagne et al. 2002; Keefer et al. 2004; Den Otter et al. 2006; Den Otter et al. 2007; Prosser et al. 2010; Arias et al. 2012)or 50 Hz (Leonard et al. 1991) and low-pass cut-off frequencies of 450 Hz (Prosser et al. 2010; Arias et al. 2012), 500 Hz (Unithan et al. 1996; Den Otter et al. 2006; Den Otter et al. 2007), 800 Hz (Lamontagne et al. 2000; Lamontagne et al. 2002), 1000Hz (Leonard et al. 1991) or 4000Hz (Keefer et al. 2004). Digital filters employed in studies also had different low and high cut-off frequencies. Low cut-off frequencies ranged from 300Hz (Hesse et al. 1999; Detrembleur et al. 2003; Massaad et al. 2010) to 500Hz (Assumpção et al. 2011; Chow et al. 2012) and high cut-off frequencies ranged from 10 Hz (Hesse et al. 1999; Lamontagne et al. 2000; Lamontagne et al. 2002; Den Otter et al. 2006; Den Otter et al. 2007; Assumpção et al. 2011; Chow et al. 2012) and 25 Hz (Detrembleur et al. 2003; Massaad et al. 2010).

A LE was digitally constructed in the majority of studies, however a wide range of smoothing parameters (low-pass filters) were used: 3 Hz (Unithan et al. 1996; Keefer et al. 2004), 6Hz (Assumpção et al. 2011), 10Hz (Chow et al. 2012), 20Hz (Damiano et al. 2000; Lamontagne et al. 2000; Lamontagne et al. 2002) and 25 Hz (Den Otter et al. 2006; Den Otter et al. 2007).

Normalization is a procedure of referencing EMG data to a standard value, allowing data comparison between muscles, across time and between subjects (Soderberg et al. 2000; Burden et al. 2003). EMG signals can be normalized using temporal and amplitude parameters. Different temporal parameters were used in the included studies: each 5% of gait cycle duration (Knutsson et al. 1979; Dietz et al. 1981); 100% of step cycle duration (Leonard et al. 1991); mean cycle duration and 100% of gait cycle

duration (Damiano et al. 2000; Lamontagne et al. 2000; Lamontagne et al. 2002; Detrembleur et al. 2003; Keefer et al. 2004; Den Otter et al. 2006; Den Otter et al. 2007). Amplitude parameters were also different across the studies: mean amplitude (Assumpção et al. 2011; Chow et al. 2012) or peak value (Knutsson et al. 1979; Dietz et al. 1981; Unithan et al. 1996; Arias et al. 2012) in each gait cycle; mean amplitude of a total of three gait cycles (Keefer et al. 2004); and, mean value or largest value of maximal voluntary contraction (MVC) (Knutsson et al. 1979; Dietz et al. 1981; Unithan et al. 1996). Lamontagne et al. (Lamontagne et al. 2000; Lamontagne et al. 2002) questioned the value of normalizing data, claiming that selection of a single maximum value could be affected by electrical noise and that the muscle activity recorded during maximal voluntary strength could be very different in healthy subjects and those with stroke. Therefore, these authors did not apply any amplitude normalization, quantifying MCo using absolute sEMG values.

Several intensity and timing parameters were considered in the analysis of sEMG during gait. The following intensity parameters were used to analyse the sEMG signal: the peak amplitude in each gait cycle (Knutsson et al. 1979; Dietz et al. 1981; Lamontagne et al. 2000; Lamontagne et al. 2002), the area of the envelope (Unithan et al. 1996; Lamontagne et al. 2000; Lamontagne et al. 2002; Detrembleur et al. 2003; Keefer et al. 2004; Assumpção et al. 2011; Arias et al. 2012; Chow et al. 2012) or a mean value of it (Damiano et al. 2000). Duration of muscle activity depends on accurate determination of the onset and offset of muscle contraction. Muscle contraction onset is a parameter used to mark the beginning of muscle activity and it was determined by using various computerized methods (Unithan et al. 1996; Hesse et al. 2000; Prosser et al. 2010; Chow et al. 2012) or by visual inspection of the sEMG signal (Detrembleur et al. 2003). Within the computerized methods, Unithan et al. (Unithan et al. 1996) determined onset when sEMG assume values between 5% and 10% above the maximum voluntary contraction value; Hesse et al. (Hesse et al. 2000) identified onset as any significant burst which achieved at least 10% of a maximum sEMG recorded and lasted at least 5% of a cycle duration; Prosser et al.(Prosser et al. 2010) determined onset periods using a Teager-Kaiser energy operator, an automatic filtering and de-noising approach; Chow et al.(Chow et al. 2012) determined onset when the sEMG signal exceeded three standard deviations of the mean. Visual

inspection, to define muscle onsets, was performed in one study by two independent raters observing graphs of previously averaged and normalized sEMG data, (Hesse et al. 1999). A consensus of opinion between both raters determined the definition of muscle temporal patterns. No information was provided about the determination of offsets in any of the included papers.

3.4. Research Question 3: Which formulas or computational approaches have been used to quantify MCo?

MCo was quantified using different formulas or computational approaches. Two different approaches were used to quantify the temporal MCo: i) the time of overlap between LE of two opposite muscles (Unithan et al. 1996; Damiano et al. 2000; Lamontagne et al. 2000; Lamontagne et al. 2002; Assumpção et al. 2011; Chow et al. 2012) and ii) the time of overlap between activity periods (onset delimited) of opposite muscles (Knutsson et al. 1979; Dietz et al. 1981; Leonard et al. 1991; Hesse et al. 1999; Detrembleur et al. 2003; Den Otter et al. 2006; Massaad et al. 2010; Prosser et al. 2010).

To quantify the magnitude of MCo, Hesse et al.(Hesse et al. 2000), Keefer (Keefer et al. 2004) and Arias et al. (Arias et al. 2012) divided the common area of the LE of antagonist muscles by the sum of the areas of those muscles. Unitham et al. (Unithan et al. 1996) divided the common area of LE between two muscles by the number of data points and Assumpção et al.(Assumpção et al. 2011) and Damiano et al.(Damiano et al. 2000) calculated the difference between the minimum and maximum values of opposite muscles in each point of the gait cycle. The amount of MCo was also measured using (i) the mean value of the area of overlap (Damiano et al. 2000), (ii) a correlation between the spectra of two opposite muscles (Wakeling et al. 2007), (iii) a quantification of the area of overlap between opposite muscles (Assumpção et al. 2011) or (iv) dividing this area by the overlap duration (Chow et al. 2012).

4. Discussion

This systematic review explored the methodologies used to assess MCo during gait in people with CNS disorders, that in most cases were stroke and cerebral palsy (Knutsson et al. 1979; Dietz et al. 1981; Leonard et al. 1991; Hesse et al. 1999; Damiano et al. 2000; Hesse et al. 2000; Lamontagne et al. 2000; Lamontagne et al. 2002; Detrembleur et al. 2003; Keefer et al. 2004; Den Otter et al. 2006; Den Otter et al. 2007; Wakeling et al. 2007; Massaad et al. 2010; Prosser et al. 2010; Assumpção et al. 2011; Chow et al. 2012). Given the considerable variability in the methods used to assess gait, analyse sEMG and quantify MCo, no recommendations can be made at this time about the most appropriate methodologies to assess MCo during gait in people with CNS disorders.

Several differences were found in the gait protocols of the included studies, including the walking speed, ground surface and duration or the distance that people walked. Walking speed is known to influence muscle activity in both healthy people and those with impairment (Hesse et al. 2001). In the majority of studies, participants were instructed to walk at their self-selected speed (Knutsson et al. 1979; Dietz et al. 1981; Leonard et al. 1991; Hesse et al. 1999; Damiano et al. 2000; Hesse et al. 2000; Lamontagne et al. 2000; Lamontagne et al. 2002; Detrembleur et al. 2003; Wakeling et al. 2007; Massaad et al. 2010; Prosser et al. 2010; Assumpção et al. 2011; Chow et al. 2012). However, as the self-selected speed of healthy subjects is obviously different from those with CNS disorders, some authors (Lamontagne et al. 2000; Lamontagne et al. 2002; Chow et al. 2012) tried to control for the influence of speed on gait pattern and match data capture conditions by instructing controls to walk at a very slow speed. However, subjects are walking under unusual circumstances which may increase postural instability (Den Otter et al. 2004) and may cause different muscle activity bursts (Lingling et al. 2010). This may not therefore be the most appropriate methodology for defining speed during gait. Self-selected gait speed for both healthy people and people with CNS disorders might be the most accurate methodology for comparing sEMG data.

Ground surface is also known to influence muscle activity. In subjects with stroke, there is a tendency to increase cadence and to induce muscle activity modifications (e.g., earlier muscle contraction onset) during treadmill walking, compared with walking on the ground (Harris-Love et al. 2004). This makes comparison between the results obtained in ground walking (Knutsson et al. 1979; Dietz et al.

1981; Damiano et al. 2000; Hesse et al. 2000; Lamontagne et al. 2000; Lamontagne et al. 2002; Detrembleur et al. 2003; Keefer et al. 2004; Wakeling et al. 2007; Assumpção et al. 2011; Chow et al. 2012) and treadmill walking very difficult (Dietz et al. 1981; Leonard et al. 1991; Unithan et al. 1996; Den Otter et al. 2006; Massaad et al. 2010; Prosser et al. 2010). There are, however, practical reasons why the different surfaces may have been selected for use with people with CNS disorders. Treadmill walking offers a more restricted space, protective bars and better monitoring conditions to enhance safety in people with poor balance (Laufer et al. 2001). However, studies using ground walking are more reflective of everyday life and may be easier and cheaper to conduct. A validation study exploring what incline grade a treadmill should be at to more closely replicate walking on a ground surface (Laufer et al. 2001; Mason et al. 2013) would be a useful future step.

Subjects with CNS disorders tend to increase their MCo magnitude to be able to walk longer or further, resulting in inefficient MCo strategies and abnormal walking patterns and potentially contributing to fatigue and muscle pain (Dean et al. 2001; Brunner et al. 2008).Recommendations to the most appropriate walking distance or time for use in sEMG studies are therefore needed.

Despite publication of the SENIAM guidelines for sensor placement procedures in 1996 (Hermens et al. 2000) and of ISEK guidelines for reporting sEMG data acquisition (Merletti 1999) and signal analysis in 1999, many studies in this review did not adhere to the recommendations nor offer justification for their lack of adherence. The fulfillment of these guidelines is determinant for the analysis of MCo, as it affects the characteristics of the sEMG signal recorded from opposite muscles (Fonseca et al. 2001).

In terms of sensor placement, the first study from this review to follow these guidelines was from 2003 (Detrembleur et al. 2003) but a further five later studies (Keefer et al. 2004; Wakeling et al. 2007; Massaad et al. 2010; Arias et al. 2012; Chow et al. 2012) did not follow the SENIAM acquisition recommendations.

In terms of signal processing analysis, the use of bandwidth amplifier filters within the range of 5 Hz to 500 Hz and the use of low pass filters at 5 or 6Hz to smooth the full-wave rectified signal, constructing a LE (Merletti 1999) were important ISEK recommendations. However, most studies in

this review used amplifier filters with characteristics different from those recommended (Merletti 1999), high-pass cut-offs at 20Hz (Lamontagne et al. 2000; Lamontagne et al. 2002; Keefer et al. 2004; Den Otter et al. 2006; Den Otter et al. 2007; Prosser et al. 2010) and low-pass cut-offs varied from 4000Hz (Keefer et al. 2004) to450Hz (Prosser et al. 2010) Only Assumpção et al. (Assumpção et al. 2011) used a 6Hz low-pass filter to construct a LE, following the recommendations (Merletti 1999). Differences in sEMG data acquisition and analysis of the included studies hinder the comparison of results across studies, therefore future research should strictly adhere to the SENIAM and ISEK recommendations or be able to offer a scientific justification for non-adherence.

There are no guidelines for the most adequate procedures for normalizing sEMG signal during gait (Burden et al. 2003). Temporal normalization was the most commonly used procedure in the included studies (Dietz et al. 1981; Hesse et al. 2000; Lamontagne et al. 2000; Detrembleur et al. 2003; Massaad et al. 2010; Assumpção et al. 2011). Temporal normalization involves defining a reference time period (e.g., each 5% of gait cycle) to enable comparison between individuals, across muscles or between trials. The use of temporal normalization alone, in the absence of any other method of normalization, has been criticized because it ignores the relative amplitude of the signal, potentially resulting in signals of inappropriate amplitudes being considered as normal (Bogey et al. 1992).

Determining the most appropriate method for normalizing sEMG amplitude is controversial. The aim of this procedure is to express the activity between muscles, across time and between individuals in relation to a reference value obtained during standard and reproducible conditions (Burden et al. 1999). Three studies recorded reference values during maximum isometric voluntary contraction (MVC) (Dietz et al. 1981; Unithan et al. 1996; Damiano et al. 2000); however, in patients with neurological conditions, this may not represent the maximum activation capacity of the muscle, resulting in increased inter-subject variation (Burden et al. 1999). The mean ensemble value (mean value reached within a period) was used in three other studies (Keefer et al. 2004; Assumpção et al. 2011; Chow et al. 2012). Mean ensemble value and peak ensemble value (maximum value reached within a period), have both been considered feasible methods for normalizing data from neurological patients (Yang et al. 1984). These methods consist of dividing each sEMG data point by the mean or

the peak value recorded from the same sEMG portion of data (Burden et al. 2003). These are more reliable methods as they have the capacity to reduce inter-subject variability(Yang et al. 1984).

The area of overlap between the LE of opposite muscles was used in eight studies (Damiano et al. 2000; Hesse et al. 2000; Lamontagne et al. 2000; Lamontagne et al. 2002; Keefer et al. 2004; Assumpção et al. 2011; Arias et al. 2012; Chow et al. 2012) to achieve a value of time or intensity of MCo during gait. The mean value of overlap could also be an important parameter for quantifying MCo (Damiano et al. 2000). An index based on the area of overlap between the LE of two opposing muscles in a specific time window was used in two studies (Unithan et al. 1996; Chow et al. 2012). A LE is a linear distribution of amplitudes at each gait cycle interval proposed (Shiavi et al. 1998) as a good method for studying synergy patterns during gait. However, various factors in the EMG measurement process might influence the establishment of representative LE´s profiles, such as electrode location, thickness of subcutaneous tissues or the system used to detect the signal (Farina et al. 2004) and therefore using amplitude parameters for comparative purposes has been criticised (Farina et al. 2004). LE repeatability can be improved by precision in electrode placement and skin preparation and by following recommendations for sEMG signal analysis (Arsenault et al. 1986; Shiavi et al. 1998): between six and ten strides , depending on the variability of each muscle assessed and an envelope filter with a cut-off frequency 8.9 Hz are recommended. However some authors (Morey-Klapsing et al. 2004; Raez et al. 2006) remain critical of the use of amplitude parameters for inter-subject comparison.

An alternative method used to quantify MCo in the studies in this review, was the estimation of time during which opposing muscles are active (Knutsson et al. 1979; Dietz et al. 1981; Shiavi et al. 1998; Detrembleur et al. 2003; Den Otter et al. 2006; Massaad et al. 2010; Prosser et al. 2010). This method depends on the accuracy of the process used to detect muscle contraction onset (Kerem et al. 2010). At least three different processes have been used: visual inspection, threshold computation and automated algorithms (Kerem et al. 2010). Variability within the automatic methods has also been found as both simple (intensity) (Unithan et al. 1996; Chow et al. 2012) and double (time and intensity) (Hesse et al. 2000) threshold methods have been used. Double-threshold methods have

some potential to eliminate false positives or delayed onset detection, however the establishment of thresholds were inconsistent across studies (Staude et al. 2001). This variability hinders the comparison of temporal MCo patterns and therefore a consensus on temporal automatic methods is needed, improving the sensitivity of the thresholds to the signal parameters.

The variability found in the methods used to estimate MCo and the lack of reliability of sEMG intensity parameters makes it difficult to compare MCo patterns between studies. Further research should therefore follow guidelines for sEMG data acquisition and analysis and reach a consensus on the temporal MCo estimation.

5. Limitations

This review was limited to studies investigating gait in people with neurological impairment in order to minimize methodological variability which would occur due to the specific requirements of different populations (Burden et al. 2003). However, further reviews on MCo during gait in other disorders such as osteoarticular (Heiden et al. 2009), ligament (Chmielewski et al. 2005) or developmental disorders (Gontijo et al. 2008) are still required. Such reviews may facilitate the generation of methodological consensus across a range of conditions. In addition, only articles written in Portuguese and English were included in this systematic review narrowing the number of eligible articles.

6. Conclusion

A systematic review was undertaken to review the literature concerning the methodologies used for measuring MCo during gait in people with neurological impairment due to CNS disorders.

It was not possible to make recommendations about the most appropriate methodologies for assessing MCo during gait in people with CNS disorders because of the considerable range of gait protocols and methods for the acquisition, analysis of sEMG and quantification of MCo. The area of overlap between the LE of opposite muscles and also the estimation of onset-delimited temporal MCo offer potential as methods for quantifying MCo. However, for improving repeatability of MCo outcomes

393 methodological criteria for sEMG data collection must be fulfilled and the automatic methods for
394 determining double-thresholds validated.
395 Given that MCo is being considered as a potential parameter to target in gait rehabilitation (Den Otter
396 et al. 2006) more robust standardized methods of evaluation and a rigorous adherence to SENIAM
397 and ISEK guidelines are required.
398
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402

Arias, P., N. Espinosa, et al. (2012). "Antagonist muscle co-activation during straight walking and its relation to kinematics: Insight from young, elderly and Parkinson's disease." Brain Research **1455**(0): 124-131.

Arsenault, A., D. Winter, et al. (1986). "Is there a 'normal' profile of EMG activity in gait?" Medical and Biological Engineering and Computing **24**(4): 337-343.

Assumpção, M., E. Piucco, et al. (2011). "Coativação, espasticidade, desempenho motor e funcional na paralisia cerebral." Motriz: Revista de Educação Física **17**: 650-659.

Bogey, R., L. Barnes, et al. (1992). "Computer algorithms to characterize individual subject EMG profiles during gait." Arch Phys Med Rehabil. **73**((9)): 835-841.

Brunner, R. and J. Romkes (2008). "Abnormal EMG muscle activity during gait in patients without neurological disorders." Gait & Posture **27**(3): 399-407.

Burden, A. and R. Bartlett (1999). "Normalisation of EMG amplitude: an evaluation and comparison of old and new methods." Medical Engineering & Physics **21**(4): 247-257.

Burden, A. M., M. Trew, et al. (2003). "Normalisation of gait EMGs: a re-examination." Journal of Electromyography and Kinesiology **13**(6): 519-532.

Busse, M. E., C. M. Wiles, et al. (2005). "Muscle co-activation in neurological conditions " Physical Therapy Reviews **7**(4): 247-253.

Chmielewski, T. L., W. J. Hurd, et al. (2005). "Perturbation Training Improves Knee Kinematics and Reduces Muscle Co-contraction After Complete Unilateral Anterior Cruciate Ligament Rupture." Physical Therapy **85**(8): 740-749.

Chow, J. W., S. A. Yablon, et al. (2012). "Coactivation of ankle muscles during stance phase of gait in patients with lower limb hypertonia after acquired brain injury." Clinical Neurophysiology **123**: 1599-1605.

Concato, J. (2004). "Observational Versus Experimental Studies: What's the Evidence for a Hierarchy?" NeuroRx. **1**(3): 341-347.

Damiano, D. L., T. L. Martellotta, et al. (2000). "Muscle force production and functional performance in spastic cerebral palsy: Relationship of cocontraction." Archives of physical medicine and rehabilitation **81**(7): 895-900.

Darainy, M. and D. J. Ostry (2008). "Muscle cocontraction following dynamics learning." Exp Brain Res **190**: 153-163.

Dean, C., C. Richards, et al. (2001). "Walking speed over 10 metres overestimates locomotor capacity after stroke." Clinical Rehabilitation **15**(4): 415-421.

Den Otter, A., A. Geurts, et al. (2004). "Speed related changes in muscle activity from normal to very slow walking speeds." Gait & Posture **19**(3): 270-278.

Den Otter, A., A. Geurts, et al. (2006). "Gait recovery is not associated with changes in the temporal patterning of muscle activity during treadmill walking in patients with post-stroke hemiparesis." Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology **117**(1): 4-15.

Den Otter, A., A. Geurts, et al. (2007). "Abnormalities in the temporal patterning of lower extremity muscle activity in hemiparetic gait." Gait & posture **25**: 342-352.

Detrembleur, C., F. Dierick, et al. (2003). "Energy cost, mechanical work, and efficiency of hemiparetic walking." Gait & posture **18**(2): 47-55.

Dietz, V., J. Quintern, et al. (1981). "Electrophysiological studies of gait in spasticity and rigidity." Brain **104**(3): 431-449.

Farina, D., R. Merletti, et al. (2004). "The extraction of neural strategies from the surface EMG." Journal of Applied Physiology **96**(4): 1486-1495.

Fonseca, S. T., P. L. P. Silva, et al. (2004). "Analyses of dynamic co-contraction level in individuals with anterior cruciate ligament injury." Journal of Electromyography and Kinesiology **14**(239-247).

Fonseca, S. T., P. L. P. Silva, et al. (2001). "Analysis of an EMG method for quantification of muscular co-contraction." Rev. Bras. Ciên. e Mov. **v. 9** (n. 3).

Gontijo, A. P. B., M. C. Mancini, et al. (2008). "Changes in lower limb co-contraction and stiffness by toddlers with Down syndrome and toddlers with typical development during the acquisition of independent gait." Human Movement Science **27**(4): 610-621.

Harris-Love, M. L., R. F. Macko, et al. (2004). "Improved Hemiparetic Muscle Activation in Treadmill versus Overground Walking." Neurorehabilitation and Neural Repair **18**(3): 154-160.

Heiden, T. L., D. G. Lloyd, et al. (2009). "Knee joint kinematics, kinetics and muscle co-contraction in knee osteoarthritis patient gait." Clinical Biomechanics **24**(10): 833-841.

Hermens, H. J., B. Freriks, et al. (2000). "Development of recommendations for SEMG sensors and sensor placement procedures." Journal of Electromyography and Kinesiology **10**(361-374).

Hesse, S., B. Brandl-Hesse, et al. (2000). "Lower limb muscle activity in ambulatory children with cerebral palsy before and after the treatment with Botulinum toxin A." Restorative Neurology and Neuroscience **17**(1): 1-8.

Hesse, S., M. Konrad, et al. (1999). "Treadmill walking with partial body weight support versus floor walking in hemiparetic subjects." Archives of physical medicine and rehabilitation **80**(4): 421-427.

Hesse, S., C. Werner, et al. (2001). "Influence of walking speed on lower limb muscle activity and energy consumption during treadmill walking of hemiparetic patients." Archives of physical medicine and rehabilitation **82**(11): 1547-1550.

Higginson, J. S., F. E. Zajac, et al. (2006). "Muscle contributions to support during gait in an individual with post-stroke hemiparesis." Journal of Biomechanics **39**(10): 1769-1777.

Keefer, D., J. Caputo, et al. (2004). "Interrelationships among thigh muscle co-contraction, quadriceps muscle strength and the aerobic demand of walking in children with cerebral palsy." Electromyogr Clin Neurophysiol. **44**((2)): 103-110.

Kerem, T., Ç. Umut, et al. (2010). "Determination of an optimal threshold value for muscle activity detection in EMG analysis." Journal of Sports Science and Medicine **9**: 620-628.

Knarr, B. A., J. A. Zeni Jr, et al. (2012). "Comparison of electromyography and joint moment as indicators of co-contraction." Journal of Electromyography and Kinesiology **22**(4): 607-611.

Knutsson, E. and C. Richards (1979). "Different types of distrubed motor control in gait of hemiparetic patients." Brain **102**(2): 405-430.

Lamontagne, A., F. Malouin, et al. (2002). "Mechanisms of disturbed motor control in ankle weakness during gait after stroke." Gait & Posture **15**(3): 244-255.

Lamontagne, A., C. L. Richards, et al. (2000). "Coactivation during gait as an adaptive behavior after stroke." Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology **10**: 407-415.

Laufer, Y., R. Dickstein, et al. (2001). "The effect of treadmill training on the ambulation of stroke survivors in the early stages of rehabilitation: A randomized study." Journal of Rehabilitation Research and Development **38**(1): 69-78.

Leonard, C. T., H. Hirschfeld, et al. (1991). "THE DEVELOPMENT OF INDEPENDENT WALKING IN CHILDREN WITH CEREBRAL PALSY." Developmental Medicine & Child Neurology **33**(7): 567-577.

Lingling, C., Y. Peng, et al. (2010). The influence of walking speed on muscle activity of thigh and application in prostheses control. IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society.

Mason, B. S., L. H. van der Woude, et al. (2013). "The ergonomics of wheelchair configuration for optimal performance in the wheelchair court sports." Sports medicine (Auckland, N.Z.) **43**(1): 23-38.

Massaad, F., T. M. Lejeune, et al. (2010). "Reducing the Energy Cost of Hemiparetic Gait Using Center of Mass Feedback: A Pilot Study." Neurorehabilitation and Neural Repair **24**(4): 338-347.

Merletti, R. (1999). "Standards for Reporting EMG data. ." Journal of Electromyography and Kinesiology **9**((1)): III-IV.

Moher, D., A. Liberati, et al. (2009). "Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement." Ann Intern Med. **151**(4): 264-269.
Morey-Klapsing, G., A. Arampatzis, et al. (2004). "Choosing EMG parameters: comparison of different onset determination algorithms and EMG integrals in a joint stability study." Clinical Biomechanics **19**(2): 196-201.
Parvataneni, K., L. Ploeg, et al. (2009). "Kinematic, kinetic and metabolic parameters of treadmill versus overground walking in healthy older adults." Clinical Biomechanics **24**(1): 95-100.
Prosser, L. A., S. C. K. Lee, et al. (2010). "Trunk and Hip Muscle Activation Patterns Are Different During Walking in Young Children With and Without Cerebral Palsy." Physical Therapy **90**(7): 986-997.
Raez, M., M. Hussain, et al. (2006). "Techniques of EMG signal analysis: detection, processing, classification and applications." Biol Proced Online. October **16**(8): 11-35.
Shiavi, R., C. Frigo, et al. (1998). "Electromyographic signals during gait: Criteria for envelope filtering and number of strides." Medical and Biological Engineering and Computing **36**(2): 171-178.
Soderberg, G. L. and L. M. Knutson (2000). "A Guide for Use and Interpretation of Kinesiologic Electromyographic Data." Physical Therapy **80**(5): 485-498.
Staude, G., C. Flachenecker, et al. (2001). "Onset Detection in Surface Electromyographic Signals:A SystematicComparison of Methods." EURASIP Journal on Applied Signal Processing(2): 67-81.
Unithan, V., J. Dowling, et al. (1996). "Cocontraction and phasic activity during GAIT in children with cerebral palsy." Electromyogr Clin Neurophysiol. **36**(8): 487-494.
Wakeling, J., R. Delaney, et al. (2007). "A method for quantifying dynamic muscle dysfunction in children and young adults with cerebral palsy." Gait & posture **25**(4): 580-589.
Winter, D. A. (2009.). Biomechanics and Motor Control of Human Movement, Whiley.
Yang, J. F. and D. A. Winter (1984). "Electromyographic amplitude normalization methods: improving their sensitivity as diagnostic tools in gait analysis." Archives of physical medicine and rehabilitation **65**(9): 517-521.

Figures and captions

Figure 1: Flow-chart according to the different phases of the systematic review as proposed by PRISMA

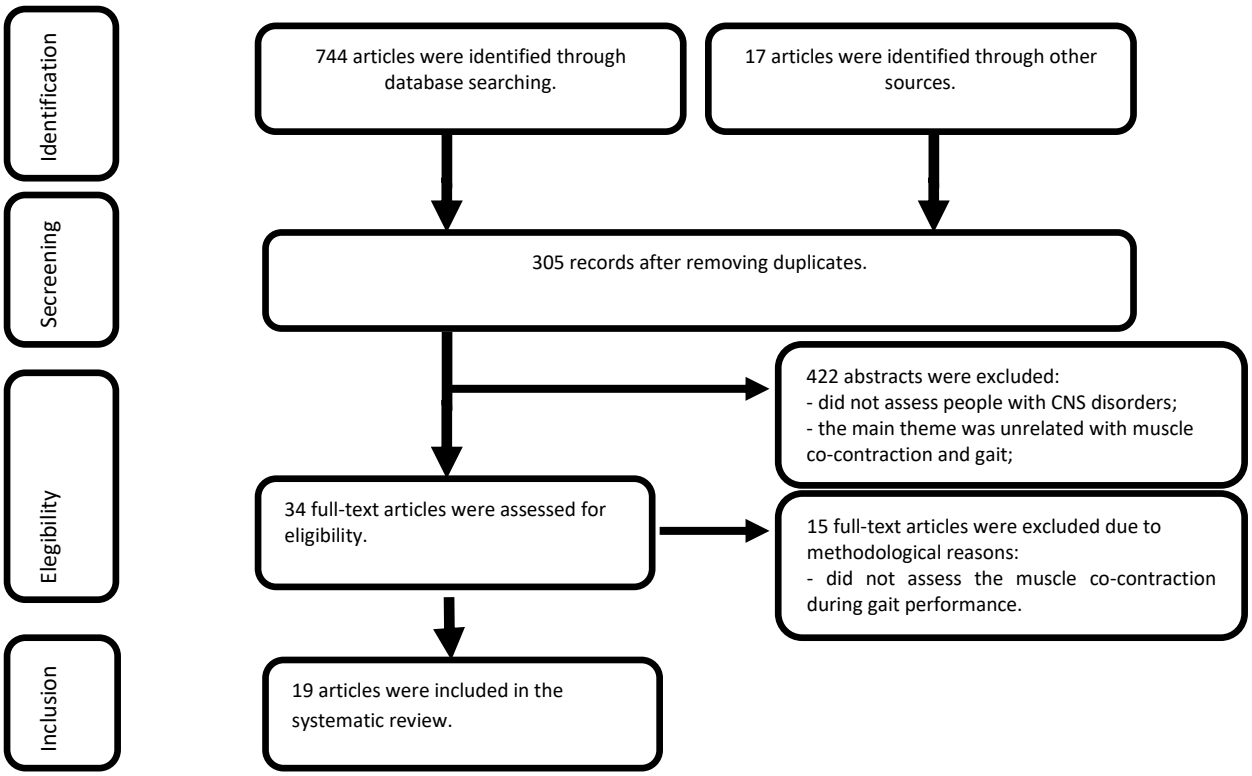

Table 1: Descriptive analysis of the studies included on this systematic review. (EMG) electromyography; (MCo) Muscle co-contraction; (MVC) maximum voluntary contraction; CMRR, common mode rejection ration, RMS, Root Mean Square.

Author (year)	Sample	Protocol to assess Walking	EMG acquisition	EMG analysis		MCo quantification	Assessed Muscles
			Electrodes location/ Skin preparation	Analogic-processing	Digital Processing		
Knutsson and Richards (1979)	Subjects with spastic hemiparetic gait (n=26); 69% males; 19-71y; Healthy subjects (n=10); 0%males; 19-31y;	Walking along 5 meters; At free speed;	Hip abductor: 3cm apart on a line perpendicular to middle fibers, mid away between trochanter major and punctum coxae; Hip adductor: electrodes 5 cm apart on a line betwenn arcus pubis and epicondylus tibialis of femur ate the proximal third of the tigh; (…)	1)Pre-amplifier a.c. (high-pass); 2)Envelope: Rectification Low pass filter at 1 Hz;	1)Normalised to the peak amplitude in each gait cycle; 2)Normalised to 5% of each gait cycle duration;	Time of antagonists muscles overlap/ each 5% of the gait cycle;	Hip abductor Hip adductor Quadriceps, Hamstrings Triceps surae Tibialis anterior
Dietz, Quinter and Berger (1981)	Subjects with spastic or rigidity gait (n=20); 60%males; 31-73y; Healthy subjects (n=20); 14-74y;	Walking on a treadmill; Walk as normal as possible, at least at 2km/hour;	Not described;	1)Envelope: Rectification Low pass filter at 50Hz;	1)Smoothed digitally; 2)Normalised to 5% of each gait cycle duration; 3) Normalised to mean value during maximum voluntary contraction;	Time of antagonists muscle activation/interval of 1/20 of one step cycle;	Gastrocnemius Tibialis anterior
Leonard, Hirschfeld and Forssberg (1991)	Children with Cerebral Palsy walking with (n=5), without support (n=3); 3months-6y; Healthy children walking with (n=2) , without support (n=3); 2months-22months;	Walking on a treadmill at a comfortable speed;	Not described;	1)Filter: High pass 50Hz Low pass 1000Hz;	1)Temporally normalized to 100% of step duration;	Time % antagonists muscle activation /step cycle;	Lateral Gastrocnemius Tibialis Anterior Biceps Femuris Vastus Lateralis Rectus Femoris Gluteus Maximus
Unithan et al. (1999)	Children with cerebral palsy (n=9); 78%males; 12,7±2,8y; Healthy subjects	Walking on a treadmill with total support in treadmill bars, supported around waist, totally unaided;	Placed in pairs, interelectrode spacing of 4 cm: over vastus lateralis, middle of the hamstrings group, tiabilais anterior and soleus; Skin preparation: shaving,	1)Pre-amplifier CMRR10MΩ; 2)Filter: High pass: 10Hz; Low pass: 500Hz;	1)Envelope: Rectification; Low-pass:3Hz 2)Normalised to the largest value observed in each muscle OR to MVC;	Index=Area of envelope overlapping between, divided by number of data points.	Vastus Lateralis Hamstrings. Tibialis Anterior Soleus

	(n=8); 78%males; 13,6±2,1y;	At 3km/h and 90% of maximum speed;	abrading and cleaning with alcohol;		3) Onset: sEMG assume values between 5% and 10% above the maximum voluntary contraction value; Offset: not clear defined;		
Hesse, Konrad, Mphil (1999)	Subjects with stroke (n=18); 77% males; 35-77y;	Treadmill (unsupported, with 15% of BWS, with 30% of BWS) and floor walking (15 meters). Mean of velocity = 0,27m/s;	Attached 2cm apart on the muscle belies; Conventional skin preparation;	1)Pre-amplifier;	1)Filter: Low-pass at 300 Hz; High-pass at 10 Hz; 2)Rectification; 3)Temporally normalized to the mean cycle duration; 4) Onset: two independent raters observing graphs of previously averaged and normalized sEMG data; Offset: not clear defined;	1)Amount of simultaneously activity between two antagonists muscles; 2)Time of simultaneously activity between two antagonists muscles;	Affected side: Tibialis Anterior Medial Gastrocnemius Biceps Femoris Vastus Latrealis Gluteus Medius Erector spinae Non affected side: Tibialis Anterior Gastrocnemius
Hesse et al. (2000)	Children with cerebral palsy (n=23); 52% males; 2-12y;	Botulinum toxin A were injected GAS; HAMS group; Children walked 10 meters (twice), at their selected speed;	Not described;	1)Pre-amplifier;	1)Temporally normalised to the mean cycle duration; 2) Onset: significant burst which achieved at least 10% of a maximum sEMG recorded and lasted at least 5% of a cycle duration; Offset: not clear defined;	Index =[(2 x <u>common area A&B</u> x 100%)/Area A + Area B]	Bilateral Gastrocnemius Tibialis Anterior Rectus Femoris Long head of Biceps Femoris;
Lamontagne, Richards and Malouin, (2000)	Subjects with stroke (n=30); 53% males; 38-81y; Healthy subjects (n=17); 52% males; 43-75y;	Walk for 10 meters; Subjects with stroke: walk at natural gait speed; Healthy subjects: walk for very slow speed;	Longitudinal placed 1 cm apart over the upper third of the tibialis anterior; over the belly of medial gastrocnemius; Skin preparation: Rubbed with alcohol;	1)Pre-amplifiers: input impedance of 10MΩ, CMRR of 93dB; 2)Filter: High-pass at 20 Hz; Low-pass at 800Hz;	1)High-pass Butterworth at 10Hz; 2)Linear Envelope: Rectification; Smoothing using a 20Hz low-pass filter; 3)Normalised to 100% of gait cycle;	Temporal Index: dividing the time of overlap between agonist and antagonist (over a threshold of 20μV) by the duration of the gait phase; averaging coactivation values of 5-10 gait cycles;	Tibialis Anterior Medial Gastrocnemius

Damiano et al., (2000)	Children with spastic Cerebral Palsy (n=10); 5-14y;	Walk barefoot down a 12-meter; .1st children walked at a freely selected speed; .2nd children walked as fast as possible, without running;	Not described; Skin preparation: Rubbed with alcohol;		1)Linear envelope: Low-pass RMS filter at 5Hz; Low-pass RMS filter at 15Hz; 2)Normalised to MVC;	Mean value of the area of overlap (the EMG minimum) of the linear envelopes of the two muscles EMG signal; Index = the minimal EMG value / maximal EMG value in each time of point;	Quadriceps Hamstrings
Lamontagne et al. (2002)	Subjects with stroke (n=30); 70% males; 37-72y; Healthy subjects (n=25); 67% males; 43-75y;	Walk along 10 meters; Subjects with stroke: at natural speed; Healthy subjects: natural and very slow speed;	Longitudinal placed 1 cm apart over the upper third of the tibialis anterior; over the belly of medial gastrocnemius; Skin preparation: Rubbed with alcohol;	1)Pre-amplifiers: input impedance of 10MΩ, CMRR of 93dB; 2)Filter: High-pass at 20 Hz; Low-pass at 800Hz;	1)High-pass Butterworth at 10Hz; 2)Linear Envelope: Rectification; Smoothing using a 20Hz low-pass filter; 3)Normalised to 100% of gait cycle;	Temporal Index = time during which an overlapping surface (threshold of 20 µV) of GAS and TA/ in each gait phase of interest; Co-contraction was averaged by 10 gait cycles;	Tibialis Anterior Medial Gastrocnemius
Detrembleur et al. (2003)	Subjects with chronic stroke (n=9); 55% males; 37-77y;	Walk across 10 meters; At a comfortable speed;	SENIAM recommendations for electrodes placement and skin preparation;		1)Rectification; 2)Filters: High-pass at 25Hz+ low-pass at-300Hz; 2)Normalised to 100% in time of gait cycle;	Temporal Index = % of gait cycle during which the antagonists muscles were co-activated;	Rectus Femoris Biceps Femoris Tibialis Anterior Lateral Gastrocnemius
Keefer, D.J., Tsch, W., Caputo, J.L., et al. (2004)	Children with spastic hemiplegic (n=13); 62%males; 11,2±3y;	Three 5-minutes walking trials at: 0.67, 0.89 and 1.12 m/s;.	Halfway between the mid-portion and distal end of the muscle; fastened with double-sided; A single reference electrode was placed over distal ulna; Skin preparation: shaved, abraded, cleaned with alcohol;	1)Pre-amplifiers: CMRR of 87dB at 60Hz; 2) Filter: High-pass at 20 Hz; Low-pass at 4000Hz;	1)Envelope: Rectification; Smoothing: Low-pass second order zero-lag Butterworth at 3 Hz; 2)Normalised to 100% in time of gait cycle; 3)Normalised to ensemble average for each muscle of three gait cycles;	Index= 2x[common area between agonist and antagonist/area of ag.+area of ant.]x100;	Vastus Lateralis Medial Hamstrings
Den Otter, et al. (2006)	Subjects with stroke (n=14); 43% males; 54,7±9,9y; Healthy subjects (n=14); 43% males; 42,8y±12,3y	Walking on a treadmill: as early as possible after admission; 1, 3, 6 and 10 weeks after baseline; Tested a maximum speed	SENIAM recommendations for electrodes placement and skin preparation;	1)Pre-amplifiers: noise level of 1µV, CMRR >95db; 2)Filter: High-pass 3rd order Butterworth (-3db, at 20Hz); Low pass 2nd order Butterworth filter (-3db, at 500Hz);	1)High pass filter at 10Hz; 2)Envelope: Rectification Low pass filter at 25Hz; 3)Normalised to 100% in time of gait cycle;	Relative amount of time that two muscles were simultaneously active (based on dichotomised signals);	Biceps Femoris Rectu Femoris Medialis Gatsrocnemius Tibialis Anterior

		(maintained during 40sec.); increased their speed as much as possible;					
Den Otter et al., 2007(Den Otter, Geurts et al. 2007)	Subjects with stroke (N=14); 42% males; 58,58±13,17y; Healthy subjects (n=14); 43% male; 42,85±12,3y;	Walking on a treadmill for 40s; Tested a self-selected speed;	SENIAM recommendations for electrodes placement and skin preparation;	1)Pre-amplifiers: noise level of 1μV, CMRR >95db; 2)Filter: High-pass 3rd order Butterworth (-3db, at 20Hz); Low pass 2nd order Butterworth filter (-3db, at 500Hz);	1)High pass filter at 10Hz; 2)Envelope: Rectification Low pass filter at 25Hz; 3)Normalised to 100% in time of gait cycle;	Relative amount of time that two muscles were simultaneously active (based on dichotomised signals);	Biceps Femoris Rectu Femoris Medialis Gatsrocnemius Tibialis Anterior
Wakeling, Delaney and Dudkieewicz (2007)	Subjects with spastic cerebral palsy (n=17); 4-21y; Healthy subjects (n=36); 3-21y;	Walked 5-10 times along 12m walkway; At their self-selected speed;	Not described;		1)Wavelet analysis; 2)Intensity spectrum;	Correlation spectra between two antagonists muscles;	Rectus Femoris Semimembranosus Medial Gastrocnemius Tibialis Anterior
Massaad, Lejeune, Detrembleur (2010) Belguium	Subjects with chronic stroke (n=10); 67% males; 47±13y;	18 training sessions: - 30 minutes walking in a treadmill with feedback of the CM displacement (3 trials, 10 minutes each); -walking period increase 5 minutes every 2 weeks; At comfortable speed;	Not described;		1)Filter: High pass at 25 Hz; Low pass at 300Hz; 2)Rectification; 3)Normalised to 100% in time of gait cycle;	Index: temporal quantified as the % of stride during which these antagonistic muscles were simultaneously activate;	Vastus Lateralis Biceps Femoris Tibialis Anterior Medial Gastrocnemius

Prosser et al. (2010)	Children with Cerebral palsy (n=15); 67% males; 25-108months; Children with typical development (n=16); 44%; 13-67,5months;	Walked barefoot down an instrumented walkway; At self-selected speed;	SENIAM recommendations for electrodes placement and skin preparation;	1)Pre-amplifier: gain of 10; 2)Filter: High pass at 20Hz; Low pass at 450Hz;	1) Filter: Low-pass Butterworth of 2nd order at 10Hz; 2) Onset: using a Teager-Kaiser energy operator, an automatic filtering and de-noising approach;	Time % antagonists muscles were simultaneously active;	Trapezius Gluteus Maximus Gluteus Medialis, Rectus Femoris Semitendinosus Erector spinae Rectus abdominis, External oblique.
Assumpção et al. (2011)	Children with cerebral palsy (n=23); 57% 7-14y; Children with typical development (n=16); 50%; 9,9-2y;	Walk along a corridor, at least during 10 seconds; At self-selected speed;	SENIAM recommendations for electrodes placement and skin preparation;	1)Pre-amplifier: CMRR of 110dB;	1)High-pass filter at 10Hz; 2)Low-pass filter at 500Hz; 3) Linear Envelope: Rectification Smoothing with filter at 6 Hz; 4)Normalised to the averaged amplitude of each muscle over the entire gait cycle;	Index = minimum EMG/Maximum EMG/each point of the gait cycle; (averaged over 5 gait cycles). Magnitude: overlap of the EMG curves between antagonist muscles;	Rectus Femoris Semitendinosus
Chow, J.W., Yablon, S.A., Stokic, D.S. (2012)	Subjects with chronic stroke (n=11) 27% males; 41±9 y; Matched healthy subjects (n=11) Gender and age matched; Subjects with TBI (n=11) Matched healthy subjects (n=11)	Walking 7 meters (8-10 times); Stroke and TBI subjects at a self-selected free speed; Healthy subjects at a self-selected very slow speed;	Cram and Kasman recommendations (1998) for electrodes placement and skin preparation;	1)Pre-amplifier: input impedance of 31KΩ, CMRR >50dB;	1)Filter: High pass at 10Hz; Low pass at 500Hz; 2)Linear envelope: Rectification; Smoothing with low-pass 2nd order Butterworth at 10Hz; 3)Normalised to the averaged amplitude of each muscle over the entire gait cycle: 4) Onset: sEMG signal exceeded three standard deviations of the mean; Offset: not clear defined;	Index = area of agonist-antagonist muscles/overlap duration; Duration = duration of overlap, as a % of the phase duration;	Medial Gastrocnemius Tibialis Anterior

Arias et al. (2012)	Subjects with Parkinson Disease (n=20) 68,25±6.85y; Young subjects (n=7) 21.86±1.46y; Elderly subjects (n=20) 66.60±7.78y;	Walking 6m long until 24m is completed: Walk at their preferred speed; Walk fast as possible; Walk matching their steps to a metronome;	Cram and Kasman recommendations (1998) for electrodes placement and ; Skin preparation: shaved, abraded and cleaned with alcohol;	1) Pre-amplifier: gain 1000; 2) Filter: High 20Hz Low 450Hz;	1) Rectification; 2) Averaging time constant of 10ms; 3) Normalised by the peak amplitude during baseline gait;	Index= the amount of overlapping activity /sum of both areas;	Tibialis Anterior Soleus

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