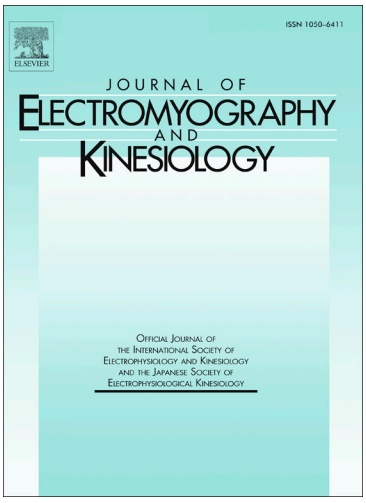

Review

Reliability of surface electromyography in estimating muscle fiber conduction velocity: a systematic review

Matteo Beretta-Piccoli, Corrado Cescon, Marco Barbero, Giuseppe D'Antona

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Reliability of surface electromyography in estimating muscle fiber conduction velocity: a systematic review.

Matteo Beretta-Piccoli* [a,b], Corrado Cescon [a], Marco Barbero [a] and Giuseppe D'Antona [b]

[a] *Rehabilitation Research Laboratory 2rLab, Department of Business Economics, Health and Social Care, University of Applied Sciences and Arts of Southern Switzerland, Manno, Switzerland.*
[b] *Criams-Sport Medicine Centre Voghera, University of Pavia, Italy*.

Keywords

surface electromyography; reliability; muscle fiber; motor unit; conduction velocity; review; systematic

* Corresponding author:
Name: Matteo
Family name: Beretta-Piccoli
Rehabilitation Research Laboratory 2rLab
University of Applied Sciences and Arts of Southern Switzerland
Department of Business Economics, Health and Social Care
CH-6928 Manno
Switzerland
Phone +41 (0) 58 666 64 29
Fax +41 (0) 58 666 64 01
E-mail: matteo.berettapiccoli@supsi.ch

Conflicts of interest
The authors declare that there are no conflicts of interest.

ABSTRACT

The purpose of this study was to review the literature (1) to determine whether surface electromyography (sEMG) is a reliable tool for estimating muscle fiber conduction velocity (CV) and (2) to identify the experimental conditions that allow highly reliable CV estimation. A literature search was performed using PubMed and Web of Science databases using the terms "reproducibility", "reliability", "agreement", "surface electromyography" and "conduction velocity". Reporting quality was assessed using the "Guidelines for the Reporting of Reliability and Agreement Studies" checklist. Seventeen papers met the eligibility criteria. Test-retest, intrasession and intersession reliability were investigated in four, three and 12 studies, respectively. Although none of the studies satisfied all the relevant quality criteria, in fifteen studies, it was possible to locate an appropriate description for up to five items of the checklist. High reliability (intraclass correlation coefficient >0.69) was reported in eight studies and was, in general, associated with using the initial or mean CV value, using several electrodes (3 to 8), ensuring appropriate electrode positioning, and evaluating muscles with fibers that run parallel to the skin. Consequently, sEMG is suitable for use when investigating CV across multiple sessions in sport science, rehabilitation, physiological and clinical studies.

1. Introduction

Muscle fiber conduction velocity (CV) is defined as the propagation velocity of action potentials along the membrane of a muscle fiber. As an important physiological parameter, CV is correlated with muscle fiber membrane properties, e.g., ion concentration, pH, muscle temperature and motor unit (MU) firing rate (Andreassen and Arendt-Nielsen, 1987, Arendt-Nielsen and Zwarts, 1989, Brody et al., 1991, Farina, 2001). Moreover, muscle fiber CV depends on the muscle fiber diameter, which is related to the fiber type (Del Vecchio et al., 2018, Hakansson, 1956). Therefore, changes in CV have been associated with the recruitment of different types of MUs (Del Vecchio et al., 2017, Masuda and De Luca, 1991, Sbriccoli et al., 2009). Moreover, alterations in muscle fiber CV are related to gradation of muscle force (Sbriccoli et al., 2003), local muscle fatigue (Merletti et al., 1990), and neuromuscular disorders (Zwarts and Arendt-Nielsen, 1988).

The increased investigation of and interest in muscle fiber CV is probably linked to the fact that it can be determined non-invasively and from a large number of concurrently detectable MUs, using surface electromyography (sEMG), during normal muscle function. The classic method of calculating CV involves estimating the delay between signals recorded at fixed distance along the direction of propagation, and the ratio between such measured distance and the estimated delay (Merletti and Farina, 2016). As two sEMG signals detected at different points along a fiber are usually not identical, there is no strict mathematical definition of the delay between them. Thus, several methods for CV estimation from sEMG recordings have been proposed (for a review, see Farina and Merletti (2004b)). The methods are all based on the assumption that signals are propagated along the muscle fibers from the innervation zone (IZ) to the tendon regions (i.e., in muscles with fibers parallel to the skin). As not all muscle fibers end in the same place, operators need to be able to identify the channels where unidirectional propagation is observed. In addition, it is important to note that when multichannel sEMG techniques are used for CV estimation, CV refers to the mean value of the different MU action potentials (MUAPs) propagating under the

electrodes at different velocities (Farina and Merletti, 2004b). The CV of individual MUs can be estimated using MUAP templates obtained via spike-triggered averaging based on the firing instants identified by decomposition of intramuscular EMG recordings (Farina et al., 2002a) and sEMG recordings (Keenan et al., 2006). Recently, Negro et al. (2016) proposed the convolutive blind source separation method, which allows the identification of tens of MUs detected using high-density sEMG (for a comprehensive review, see Farina et al. (2016)). Estimation of the CV from a MUAP template is relatively simple, but it is considerably more complex for an interferential signal, which is the sum of the contributions of different asynchronously appearing MUs (Farina and Merletti, 2000).

Many factors other than the physiological phenomena under study bias the estimation of CV during voluntary contractions. In fact, the detection system's features, such as the electrode positioning, interelectrode distance (IED), number of electrodes, and algorithm used (Farina et al., 2002b, Farina and Merletti, 2000, 2003, 2004b, Farina et al., 2001), directly influence the CV estimations. Furthermore, to reduce the effect of cross-talk from nearby muscles or to "isolate" the investigated muscle from the central nervous system, selective electrical stimulation of a nerve branch or of the motor point may be applied. Electrically evoked myoelectrical signals allow easier estimation of the muscle fiber CV from a MU pool, which is likely to lead to a more stable estimation than an estimation based on voluntary contractions (Botter et al., 2009, Merletti et al., 1992).

In addition, the estimation of muscle fiber CV during dynamic exercise has become possible due to the development of multichannel adhesive arrays of electrodes (Pozzo et al., 2004) and a novel data processing algorithm that allows CV estimation based on short signal epochs (Farina et al., 2004a). This method has helped to overcome the problems previously associated with CV estimation during dynamic exercise (which were exhaustively discussed in a study by Merletti and Farina (2016)), such as movement artifacts (Clancy et al., 2002) and signal non-stationarity (Merlo et al., 2005). Moreover, the evaluation of muscle fiber CV has gained the attention of researchers and clinicians interested in understanding the neuromuscular system modifications caused by disease (Allen et al.,

2008, Bazzichi et al., 2009, Blijham et al., 2006, Boccia et al., 2016, Butugan et al., 2014, Campanini et al., 2009, Meijer et al., 2008, Minetto et al., 2011), pain (Falla and Farina, 2005, Klaver-Krol et al., 2012) and fatigue (Gonzalez-Izal et al., 2012). For instance, the CV value may be used to supplement information obtained at the muscle fiber level with intramuscular EMG, which is the clinical standard for neurological assessments, allowing the firing pattern of single MUs to be reliably studied and the shape of intramuscular potentials to be investigated, which is critical for the diagnosis of several neuromuscular diseases (Drost et al., 2006). Recently, several studies in the field of sport science have focused on possible relationships between CV and cardiorespiratory responses during dynamic exercise (e.g., Kilen et al., 2012, Lenti et al., 2010, Pereira et al., 2013, Stewart et al., 2011).

The assessment of the reliability of CV (measured using sEMG) is of considerable relevance, as it is important to be confident that changes in estimated muscle fiber CV are associated with real physiological events and not with measurement errors. Thus, the aims of this systematic review were (1) to verify whether muscle fiber CV may be reliably estimated during voluntary and electrically elicited contractions using sEMG and (2) to identify the experimental conditions that allow highly reliable CV estimation.

2. Methods

A systematic review of studies reporting on the reliability and/or reproducibility of sEMG for assessing muscle fiber CV was performed according to the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) statement (Moher et al., 2009). A detailed protocol was written a priori and is available at https://www.crd.york.ac.uk/prospero/ (CRD42018092421).

2.1 Identification of studies

On April 20, 2018, a comprehensive search of the databases MEDLINE (PubMed) and Web of Science was conducted. The search string for MEDLINE involved the following medical subject

heading (MeSH) terms and free-text terms: [[Reproducibility of Results (MeSH) AND Electromyography (MeSH)] AND conduction velocity], whereas Web of Science was searched using the following search string: [surface electromyography OR surface-electromyography OR surface EMG OR sEMG] AND [conduction velocity] AND [reliability OR reproducibility OR agreement]. No restrictions were applied regarding the publication date or the language of the articles. All hits obtained using the search strategies were exported to EndNote X8 (Clarivate Analytics, Philadelphia, PA, USA), and duplicates were then removed.

2.2 Study selection

Two reviewers (MBP and CC) independently screened the titles and abstracts of the resulting studies and identified those that satisfied the inclusion and exclusion criteria (see Section 2.3). If it was not clear whether an article should be included based on the title and abstract, the full text was inspected. Moreover, controversies between the reviewers regarding the eligibility of titles/abstracts or full texts were solved in a consensus meeting involving the two reviewers. If a consensus could not be reached, a third reviewer (MB) was asked to make the final decision.

2.3 Eligibility criteria

Studies that fulfilled all of the following inclusion criteria were eligible for inclusion in this review: (1) full-text article published in peer-reviewed journal; (2) longitudinal study with a repeated-measures experimental design; (3) investigated reliability or reproducibility of sEMG for assessing CV; (4) used sEMG to estimate CV. In addition, we excluded studies that fulfilled at least one of the following criteria: (1) used mathematical models; (2) used needle/intramuscular EMG; (3) estimated CV of nerve signal; (4) used animal models. Studies that met the eligibility criteria formed the final sample, and two reviewers (MBP and CC) independently assessed the reporting quality.

2.4 Reporting quality assessment

Each included study was assessed using the Guidelines for Reporting Reliability and Agreement Studies (GRRAS) checklist, which is a 15-item checklist designed to determine the reporting quality of reliability studies (see Appendix B). The GRRAS checklist was developed in 2011 by Kottner et al. (2011) to improve the quality of reporting in reliability and agreement studies in the healthcare and medical field, as no established standards were previously available. The items overlap with the Standards for Reporting of Diagnostic Accuracy (STARD) (Bossuyt and Reitsma, 2003) and the Standards for Educational and Psychological Testing (American Educational Research Association et al., 1999).

Studies were not given an overall numeric quality score. Instead, each item was considered separately, and the page number of the page containing an appropriate description was noted, if applicable. A chart involving three categories (reported, not reported or inapplicable) was then constructed.

2.5 Data extraction

The following information related to sEMG methodology was extracted from the studies: sEMG electrode description (type, size, inter-electrode distance and electrode positioning); a priori identification of the muscle IZ or motor point; muscle contraction type (voluntary or electrically elicited) and intensity; signal type (interferential or single potential); sEMG signal detection derivation (monopolar or single differential); CV estimation method and interval of acceptance of the physiological range of CV values; extracted CV parameters (i.e., initial value, slope [rate of change] and area ratio). Based on the study by Merletti et al. (1990), the initial CV value and slope were defined as follows. First, a regression line of CV over time was estimated using the CV estimates obtained from each signal epoch. Thereafter, the intercept with the *y*-axis and rate of change of the regression line were used to define the initial CV value and slope, respectively.

Next, the following study characteristic data were extracted: test-retest period, whether the electrodes were repositioned and relative and absolute reliability values (see Appendix A). The criteria used for the interpretation of the relative reliability correlation coefficients were as follows:

I. Intraclass correlation coefficient (ICC): 0.00–0.25: very low; 0.26–0.49: low; 0.50–0.69: moderate; 0.70–0.89: high; 0.90–1.00: very high reliability (Munro, 2005).

II. Pearson's correlation coefficient (r): 0.00–0.19: very weak; 0.20–0.39: weak; 0.40–0.59: moderate; 0.60–0.79: strong; 0.80–1.00: very strong correlation (Evans, 1996).

The data were extracted by a reviewer (MBP) and double-checked for accuracy by another reviewer (CC).

2.6 Grouping of studies

A previous literature analysis showed that terms such as "reliability," "repeatability," "reproducibility," "consistency" and "agreement" have been used interchangeably (Atkinson and Nevill, 1998). For this reason, we defined three categories of reliability study: (1) test-retest reliability (i.e., repeated measurements within one day, without electrode replacement); (2) intrasession reliability (i.e., repeated measurements within one day, with electrode replacement); and (3) intersession reliability (i.e., repeated measurements separated by at least one day, with electrode replacement).

3. Results

Please insert Figure 1 about here

3.1 Literature search

Figure 1 shows a flowchart of the processes regarding study retrieval, screening and eligibility assessment. The literature search yielded 89 potentially eligible articles on CV assessment using EMG. Of these, 72 were excluded based on the title/abstract or full text, leaving 17 articles that met all the eligibility criteria (Beretta-Piccoli et al., 2018, Beretta-Piccoli et al., 2017, Falla et al., 2002,

Farina et al., 2004b, Harba and Teng, 1999, Hogrel et al., 1998, Linssen et al., 1993, Macaluso et al., 1994, MacDonald et al., 2008, Martinez-Valdes et al., 2016, Martinez-Valdes et al., 2017, McIntosh and Gabriel, 2012, Merletti et al., 1998, Merletti et al., 1995, Ollivier et al., 2005, Rainoldi et al., 2001, Rainoldi et al., 1999). A single discrepancy between reviewers about the inclusion of one of the studies (Macaluso et al., 1994) was resolved by discussion. Table 1 shows the study details, with the studies listed in chronological order from 1993 to 2018. The most frequent reasons for exclusion were: muscle fiber CV was not assessed; lack of reliability data or appropriate reliability study design; and needle EMG or mathematical simulations were used to evaluate CV (Figure 1).

3.2 Study characteristics

1. Subjects, muscles and contractions

The number of participants in the studies varied from three to 40. The following muscles were investigated to assess CV reliability during isometric constant force contractions: biceps brachii (BB; n=7), vastus medialis, vastus medialis obliquus and/or vastus lateralis (VM, VMO and VL; n=5), tibialis anterior (TA; n=2), sternocleidomastoid and anterior scalene muscles (SCM and AS; n=1) and anterior temporal muscle (ATM; n=1). The study by MacDonald et al. (2008) investigated CV reliability during cyclic movements of the vastii muscles (Table 1).

2. Electrode characteristics, positioning and CV estimation

In 11 studies, myoelectric signals were detected using linear electrode arrays in single differential (SD) configuration, whereas in the other six, bi-dimensional arrays in SD or monopolar configuration were used. Electrode positioning, except in the study by Macaluso et al. (1994), involved considering anatomical landmarks and, in 12 studies, the IZ (or motor point) position on the muscle belly was defined. Electrode repositioning occurred in all the studies except the study by Macaluso et al. (1994). However, electrode repositioning only occurred partially in the studies by

Hogrel et al. (1998) and Beretta-Piccoli et al. (2018), which both used multiple experimental designs. In eight out of 16 studies, to improve the reliability and reduce the displacement error, the position of the electrode array was marked on the skin.

CV was computed with the fast Fourier transform algorithm (Linssen et al., 1993), the cross-correlation method (Harba and Teng, 1999, Hogrel et al., 1998, Macaluso et al., 1994, McIntosh and Gabriel, 2012, Ollivier et al., 2005), the discrete Fourier transform-based alignment algorithm developed by McGill and Dorfman (1984) (Falla et al., 2002, Merletti et al., 1998, Merletti et al., 1995, Rainoldi et al., 2001, Rainoldi et al., 1999) or the multichannel maximum-likelihood algorithm developed by Farina et al. (2004b) (Beretta-Piccoli et al., 2018, Beretta-Piccoli et al., 2017, Farina et al., 2004b, MacDonald et al., 2008, Martinez-Valdes et al, 2016, Martinez-Valdes et al., 2017) (Table 2).

Please insert Figure 2 about here

3.3 Quality of reporting

Studies were classified depending on how compliant they were with respect to the GRRAS checklist. The reviewers classified items 4, 6, 7, 9 and 12 (out of 15) as inapplicable to the included studies, as the number of raters and their characteristics are usually only relevant in clinical studies. Additionally, information about the sample size (item 6) was disregarded in all the studies, as the all investigated reliability in relatively small groups, with the number of participants varying from three to 40. Although none of the studies satisfied all the relevant criteria for reporting quality (Figure 2), most were compliant with many of the checklist items: in 15 studies, it was possible to locate an appropriate description of up to five items out of 10. The studies by Merletti et al. (1995) and Rainoldi et al. (1999) had the best quality, whereas the studies by Harba and Teng (1999) and Beretta-Piccoli et al. (2018) had the lowest.

Several studies were lacking regarding one or more of the following minor points:

- Item 1: 13 studies did not mention the type of reliability (i.e., test-retest, intrasession or intersession) investigated in the title/abstract (Beretta-Piccoli et al., 2018, Falla et al., 2002, Farina et al., 2004b, Harba and Teng, 1999, Linssen et al., 1993, Macaluso et al., 1994, MacDonald et al., 2008, Martinez-Valdes et al., 2017, McIntosh and Gabriel, 2012, Merletti et al., 1998, Ollivier et al., 2005, Rainoldi et al., 2001, Rainoldi et al., 1999).
- Item 3: as the included studies were conducted with healthy subjects only, 10 studies did not specify the subject population of interest, leaving it implied (Beretta-Piccoli et al., 2018, Farina et al., 2004b, Harba and Teng, 1999, Hogrel et al., 1998, MacDonald et al., 2008, Martinez-Valdes et al., 2016, Martinez-Valdes et al., 2017, McIntosh and Gabriel, 2012, Ollivier et al., 2005, Rainoldi et al., 2001).
- Item 15: only three studies (Martinez-Valdes et al., 2017, Rainoldi et al., 2001, Rainoldi et al., 1999) provided supplementary materials in an appendix.

Several studies were lacking regarding the following items, which were considered to represent major issues:

- Item 10: in two studies (Harba and Teng, 1999, Macaluso et al., 1994), the statistical approach used to evaluate the reliability of CV was not described sufficiently to allow repetition of the study by other researchers.
- Item 11: five studies (Beretta-Piccoli et al., 2018, Beretta-Piccoli et al., 2017, MacDonald et al., 2008, Martinez-Valdes et al., 2016, Martinez-Valdes et al., 2017) did not mention, in the Results section, whether it was possible to estimate CV in all the participants.
- Item 13: five studies (Beretta-Piccoli et al., 2018, Harba and Teng, 1999, Hogrel et al., 1998, Macaluso et al., 1994, Ollivier et al., 2005) did not report a combination of reliability coefficients, which makes it difficult to form a detailed impression of the degree of reliability.

3.4 Reliability results

The diversity among the included studies precludes a simple synthesis of the results. Thus, the studies were grouped according to the reliability design (Table 3):

1) Hogrel et al. (1998) reported good within-location *test-retest reliability* (i.e., without electrode replacement) for CV estimates at L_0 (the electrode location where CV was minimal, when averaged over all contraction conditions) in the VL.

Martinez-Valdes et al. (2016) reported high to very high *test-retest* and *intersession reliability* (ICC up to 0.97; SEM $\leq$ 0.11) for the initial MU CV value, estimated using bi-dimensional arrays, monopolar EMG derivation and MU decomposition techniques. High reliability was found at all the isometric contraction levels in the VL and VM. Furthermore, the study by Beretta-Piccoli et al. (2018) evaluated *test-retest reliability* (1-hour delay between measurements, without electrode repositioning) and *intersession reliability* (1-week delay between measurements) in the BB. They obtained very high ICC values for *test-retest reliability* (>0.9). However, for *intersession reliability*, the ICC values regarding the initial CV value were much lower (0.04–0.79), and the ICC value depended on the contraction level (the higher the maximum voluntary contraction [MVC, %], the lower the ICC). Unfortunately, Macaluso et al. (1994) did not succeed in measuring the CV in the ATM.

2) Harba and Teng (1999) and Merletti et al. (1998, 1995) investigated the *intrasession reliability* of CV. Harba and Teng evaluated the reliability of CV measured at different locations in the BB, with a custom-made linear array, using the relative variance (R%), which is defined as the squared coefficient of variation. Nevertheless, their results suggest that it was not possible to obtain the exact same CV value using the cross-correlation technique. The authors found CV variations over time of up to 5.4% (in terms of R%), when the electrode location, IED and signal epoch were fixed. When different electrode locations were investigated, and the IED was fixed, the CV variations were up to ± 0.75 ms^{-1}. An increase in the time delay (when the electrodes were more widely spaced) resulted in more consistent CV estimates. The studies by Merletti et al. (1998, 1995) examined the reliability of muscle fiber CV estimates, slope and area ratio after electrically eliciting

contractions in the VM and TA muscles. Their results showed the low reliability of CV based on the ICC values although, in general, the Pearson's r values were high.

3) Finally, the other 10 studies (Beretta-Piccoli et al., 2017, Falla et al., 2002, Farina et al., 2004b, Linssen et al., 1993, MacDonald et al., 2008, Martinez-Valdes et al., 2017, McIntosh and Gabriel, 2012, Ollivier et al., 2005, Rainoldi et al., 2001, Rainoldi et al., 1999) investigated the *intersession reliability* of CV. Moderate to high reliability scores (ICC 0.7–1), of either CV or slope estimates, were reported by six studies (Beretta-Piccoli et al., 2017, Farina et al., 2004b, Linssen et al., 1993, Martinez-Valdes et al., 2017, McIntosh and Gabriel, 2012, Ollivier et al., 2005, Rainoldi et al., 2001). Rainoldi et al. (2001) also evaluated the reliability of CV using the Fisher test (F) ratio between the mean squared error (MSE) due to the subject's differences and the sum of the MSE due to trial and day variations, and they obtained similar results.

Furthermore, both relative and absolute reliability of CV were evaluated in 12 out of 17 studies (of these 12, one assessed test-retest reliability, one assessed intrasession reliability and 10 assessed intersession reliability). The following coefficients were used to assess relative and absolute reliability:

- relative reliability: ICC (n=13 studies); Pearson's r (n=3); analysis of variance (ANOVA)-based Fisher test, F (n=1) (Atkinson and Nevill, 1998);
- absolute reliability: standard error of the mean, SE (n=5); standard error of measurements, SEM (n=5); coefficient of variation, CoV (n=4); square CoV (n=1); minimal detectable change, MDC_{95} (n=1); Bland & Altman 95% limits of agreement, LoA (1986) (n=2).

In the study by Hogrel et al. (1998), median reliability was assessed, without using a particular coefficient (Table 3).

Generally, a higher degree of reliability was found more often in the more recent studies, in association with the use of bi-dimensional arrays, reduced IED, multichannel algorithms and, in particular, in association with the use of the initial CV value.

4. Discussion

In this systematic review, we aimed to synthesize the evidence concerning the reliability of sEMG for assessing muscle fiber CV. Seventeen studies met the inclusion criteria and were reviewed. Despite several methodological flaws identified in the included studies, which are discussed later on, the results of this review indicate that sEMG is a reliable tool for estimating CV in muscles with relatively long fibers that are parallel to the skin surface. There was great variability in the experimental conditions (e.g., isometric or dynamic conditions in various muscles, with various acquisition systems and CV estimation methods using interferential signals or single potentials), and in the test-retest periods (ranging from 4 minutes to 2 weeks). The more recent studies showed a higher degree of reliability (ICC up to 0.9; Table 3). Moreover, the results suggest that the mean and initial CV values are generally the most reliable extracted parameters (compared to the slope and area ratio), with higher ICC and lower absolute reliability values, suggesting that the mean and initial CV values are sufficiently accurate for clinical applications.

Nevertheless, a major aspect of using sEMG to estimate CV is the operator-dependent nature of the CV estimates, though this was not considered in any of the 17 studies. For instance, muscle fiber CV estimation during isometric contractions and, in particular, dynamic contractions is strongly affected by the electrode positioning. Before placing the electrodes, attention should be paid to the guidelines suggested by the "Surface EMG for a Non-Invasive Assessment of Muscles" (SENIAM) project (Hermens et al., 2000) and to descriptions of the IZ locations in superficial muscles (Barbero et al., 2012, Beretta Piccoli et al., 2014). Moreover, due to the anatomical variability of the IZ, while an optimal or highly reliable method regarding electrode placement may exist for specific muscles and specific subjects, there is no optimal method for the same muscle in different populations or different muscles in the same subject.

4.1 Reporting quality assessment

The overall reporting quality of the included studies (five GRRAS checklist items were considered inapplicable) was in general between moderate and good. Although the majority of the item results are self-explanatory, the following points are notable:

Item 1: 13 studies did not mention in the title/abstract which types of reliability (test-retest, intrasession and/or intersession) were selected to investigate CV. This lack only partially affects the MEDLINE search as, in the hierarchical classification of MeSH terms, the entry term *reliability* refers to the MeSH term "reproducibility of results" (which was used in the search string), which also includes "test-retest reliability," but not "intrasession" or "intersession." Moreover, in the Web of Science database, the terms "test-retest,", "intrasession" and "intersession" are not indexed. Therefore, since the primary resources for searching evidence are internet and the bibliographic resource, authors should use the MeSH terms explicitly in the title/abstract as suggested in (Kottner et al. (2011).

Item 5: the reviewers agreed to consider item 5 (which requires the information that is already known about reliability and agreement to be described) as inapplicable to the studies by Macaluso et al. (1994) and Martinez-Valdes et al. (2017), as the two studies were pioneer investigations and thus were not required to provide an overview of existing reliability evidence.

Item 10: the statistical methods selected to analyze reliability were heterogeneous, ranging from Pearson's r to the Bland & Altman plot. Moreover, the early studies assessed only one type of reliability (relative or absolute). Additionally, two studies (Harba and Teng, 1999, Macaluso et al., 1994) did not accurately describe their statistical methods or the reason why a certain approach was chosen.

Item 13: Due to the very broad spectrum of statistical approaches that can be adopted, the GRRAS recommends reporting at least one combination of reliability coefficients, e.g., measures of relative and absolute reliability, to allow a better interpretation of the calculated values. In five studies (Beretta-Piccoli et al., 2018, Harba and Teng, 1999, Hogrel et al., 1998, Macaluso et al., 1994,

Ollivier et al., 2005), the Results sections provided only limited information about the reliability tests, making the reliability results more difficult to comprehend and interpret.

4.2 Reliability assessment

In the medical literature, at least two critical issues regarding reliability studies have been identified:

1) The term "reliability" has been used interchangeably with "repeatability," "reproducibility," "consistency," "agreement," "concordance" and "stability," with varying degrees of consistency (Atkinson and Nevill, 1998, Bartlett and Frost, 2008).

2) Many statistical tests have been used to assess reliability, and no single approach can be regarded as standard (Dunn et al., 2004). Despite this, the recommendations in the GRAAS (Kottner et al. 2011) suggest reporting at least one combination of coefficients (e.g., ICC and SEM), which should allow the reader to form a more detailed impression of the degree of reliability. For instance, the reliability results expressed using Pearson's r in this systematic review should be treated carefully, as this coefficient only gives information about the degree of association between repeated measures. Moreover, it cannot detect systematic errors: high correlation does not mean high reliability (Bruton et al., 2000).

4.2.1 Test-retest reliability

Very high test-retest reliability (ICC > 0.9) of initial CV values estimated using interferential signals in the BB was reported in the study by Beretta-Piccoli et al. (2018). Moreover, the study by Martinez-Valdes et al. (2016) also reported mostly very high levels of reliability (ICC > 0.8) for MU CV estimated using surface multichannel single potentials in the vastii muscles. High reliability was independent of force intensity in both studies.

4.2.2 Intrasession reliability

Two studies reported low intrasession reliability of initial CV values, normalized slopes and area ratios (ICC < 0.45) estimated from compound potentials in muscles of the lower limb (Merletti et al., 1995, 1998). A third study, by Harba and Teng (1999), also reported intrasession reliability but, as reliability was not expressed in terms of ICC, or Pearson's r, it was not possible to compare the reliability results with those of the other studies.

4.2.3 Intersession reliability

Seven out of 12 studies (including studies with multiple designs for assessing reliability) showed high intersession reliability of CV estimated from compound potentials (ICC > 0.8) and interferential signals (ICC > 0.7) in lower and upper limb muscles, mainly at force levels ≥ 50% MVC. Low absolute reliability estimators for CV and slope values (within-subjects normalized SE < 10% and SEM ≤ 0.11) suggest that these parameters are sufficiently accurate and suitable for clinical applications (Table 3).

4.3 Conditions for reliable CV estimation

The authors of the included studies identified several factors that may affect the reliability of the CV estimation, ranging from the muscle architecture to the algorithm used. In this section, the most relevant conditions for highly reliable CV estimation are summarized.

a) Muscle characteristics and contraction type

The muscles from which CV was reliably estimated were limited in number, but included the VL and VM/VMO (Martinez-Valdes et al., 2016, Martinez-Valdes et al., 2017, Rainoldi et al., 2001), BB (Beretta-Piccoli et al., 2018, Beretta-Piccoli et al., 2017, Farina et al., 2004b, Ollivier et al., 2005) and TA (McIntosh and Gabriel, 2012). The common anatomical features of these muscles are the presence of relatively long fibers arranged in a plane parallel to the skin, with IZs concentrated in a small muscle region. In addition to isometric contractions, these features are particularly

relevant when dynamic contractions are performed (e.g., MacDonald et al., 2008) as, during movement, the IZ shift and muscle shortening limit the portion of fiber semi-length in which propagating signals can be detected (Farina et al., 2004a). Notably, in pinnate or fusiform muscles with multiple IZs, the CV cannot be estimated reliably (Barbero et al., 2012).

b) Electrode locations and positioning

The issue of electrode locations (as well as repositioning before each experiment) was identified as the most critical factor influencing the reliability of CV estimation in all the included studies. For instance, in the study by Hogrel et al. (1998), the authors identified two "muscular critical zones" that must be avoided. A systematic overestimation of CV occurred in these regions, i.e., when myotendinous junctions and/or neuromuscular junctions were in the detection volume. Moreover, reliable CV estimation requires careful orientation of the electrodes along the muscle fibers. This issue was investigated by McIntosh and Gabriel (2012), who proposed a novel procedure to help operators orient the electrodes, which resulted in highly reliable CV estimates. Furthermore, the development of accurate electrode positioning criteria (based on the localization of the IZs) is recognized as vital for achieving standardization of sEMG methodology (Falla et al., 2002). The identification of these criteria represent the main goal of the standardization process initiated with European Concerted Action – "Surface EMG for a Non-Invasive Assessment of Muscles" (SENIAM) and continued with the publication of "Atlas of Muscle Innervation Zones" (Barbero et al., 2012), which suggests appropriate electrode positions when a single electrode pair is used.

In addition, when using electrode arrays, visual inspection is needed to select the channels between the IZ and tendons, where the MUAPs appear similar in shape and shifted in time (Beretta-Piccoli et al., 2018, Beretta-Piccoli et al., 2017, Farina et al., 2004b, Martinez-Valdes et al., 2016, Martinez-Valdes et al., 2017).

c) IED and number of channels

The selection of the distance between detection points is critical, and it greatly depends on the semi-fiber length. Thus, it is not possible to suggest an optimal IED that applies to all muscles. Nevertheless, the reliability of CV estimates increases with an increasing number of signals and an increasing IED, between 5 and 10 mm (Farina et al., 2004b, McIntosh and Gabriel, 2012, Ollivier et al., 2005, Rainoldi, 2001). As, an IED of 5 mm may be more affected by minor electrode displacements and local tissue dishomogeneities (Merletti et al., 1995), small electrodes (diameter < 3 mm) with small IED (< 10 mm) have to be recommended in order to avoid the spatial aliasing (Afsharipour et al., 2015 and 2019). Therefore, using multichannel sEMG with between four and eight electrodes and 5 mm IED, can help to increase the reliability of CV (Beretta-Piccoli et al., 2018, Beretta-Piccoli et al., 2017, Farina et al., 2004b, MacDonald et al., 2008, Martinez-Valdes et al., 2016, Martinez-Valdes et al., 2017).

d) CV estimation method

Among the factors affecting the reliability of CV estimates, the estimation method has an impact. In fact, before the study by Farina et al. (2004b), in which bi-dimensional arrays of electrodes and the multichannel maximum-likelihood algorithm were used, a highly reliable estimation of CV was achieved only once, in the study by Rainoldi et al. (2001). This was done using the discrete Fourier transform-based algorithm (McGill and Dorfman, 1984) and a four-bar linear electrode array. Furthermore, the cross-correlation analysis of two delayed signals (Naeije and Zorn, 1983) may be applied to reliably estimate muscle fiber CV when using a three- or four-electrode system (McIntosh and Gabriel, 2012, Ollivier et al., 2005) , anyway this method requires interpolation, which requires a spatial sampling frequency is above the Nyquist rate (Afsharipour et al 2019).

Nonetheless, the most reliable and robust methods are those based on maximum-likelihood estimation in the frequency domain (Farina et al., 2001), which provide higher velocity resolution and lower variance than other approaches (Farina and Merletti, 2004b). Further developments and adaptations of the maximum-likelihood algorithm (Farina and Merletti, 2004a, Farina et al., 2004a)

have allowed highly reliable estimates of muscle fiber CV and CV associated with single MUs to be obtained during isometric and dynamic contractions, using multichannel sEMG involving interferential and single potential signals (Beretta-Piccoli et al., 2018, Beretta-Piccoli et al., 2017, MacDonald et al., 2008, Martinez-Valdes et al., 2016, Martinez-Valdes et al., 2017).

e) CV parameters

Initial and mean CV values were the most reliable parameters in eight studies (Beretta-Piccoli et al., 2018, Farina et al., 2004b, MacDonald et al., 2008, Martinez-Valdes et al., 2016, Martinez-Valdes et al., 2017, McIntosh and Gabriel, 2012, Ollivier et al., 2005, Rainoldi et al., 2001), whereas the slope was associated with a high degree of reliability only once, during fatiguing isometric contractions of the BB (Beretta-Piccoli et al., 2017). The estimation of the muscle fiber CV slope may be useful to characterize the peripheral components of muscle fatigue (Arendt-Nielsen et al., 1989, Bigland-Ritchie et al., 1981). Furthermore, if the MU pool is stable, this variable correlates with fiber size and type (Sadoyama et al. 1988).

In seven studies (Falla et al., 2002, Farina et al., 2004b, Merletti et al., 1998, Merletti et al., 1995, Ollivier et al., 2005, Rainoldi et al., 2001, Rainoldi et al., 1999), CV slopes were not as reproducible as the initial CV values, reflecting the high sensitivity of CV slope to electrode repositioning in retest sessions. Notwithstanding, the promising result of Beretta-Piccoli et al. (2017), regarding the high degree of reliability of slope estimates, may be related to the reduction in noise associated with the use of bi-dimensional arrays with a 10-mm IED (which allows a larger number of electrodes and an optimal distance between detection points, and which lowers the sensitivity to electrode displacement).

However, it should be noted that as CV slopes depend on fatigability, their reproducibility also depends on the reproducibility of the fatiguing protocol and of the subject's fatigability conditions. Good reproducibility of such variables is very difficult to achieve. Additional studies are needed to

investigate whether muscle fiber CV slope calculated using multichannel recordings in various superficial muscles with fibers parallel to the skin is a reliable parameter.

f) Operator

Importantly, the issue is not simply the reliability of sEMG itself for assessing CV, but also the training and expertise of the operator regarding the use of this technique to correctly detect, process and interpret sEMG signals (Barbero et al., 2012). For example, visual inspection to select the appropriate number of channels of a bi-dimensional electrode array, to be used for CV estimation, is still needed. Operators should be able to identify movement artifacts, missing channels or the presence of large sinusoidal components at 50 Hz, which must be dealt with before the analysis.

5. Study limitations

i) The lack of standardized reporting across the reliability studies (probably partly because the GRRAS checklist was only published in 2011) combined with the poor statistical analysis descriptions (particularly in the early studies) limited the data extracted for use in this systematic review. Adequate reporting regarding the methodology used in reliability studies should be encouraged. Reporting can often be affected by the word count restrictions imposed by journals at the time of publication. However, inadequate reporting affects the comparison of results between studies and restricts the synthesis of evidence.

ii) The included studies considered only six muscles when investigating the reliability of CV: BB (n=7), VL and VM (n=5), TA (n=2), SCM (n=1) and AS (n=1). Therefore, the conclusions of this systematic review may only be applicable to these muscles and may not be generalizable to other muscles.

iii) Most studies analyzed the reliability of CV estimation during isometric contractions as opposed to functional activities (only one study analyzed dynamic contractions, which involved cyclic

movements of the vastii muscles (MacDonald et al., 2008)). Therefore, the results of this review are not generalizable to dynamic conditions other than cyclic.

6. Conclusions

Since the publication of the recommendations by Farina et al. (2004b) regarding the appropriate number of electrodes and IED, along with visual channel selection and the use of the maximum-likelihood algorithm, the results of studies investigating the reliability of CV estimation in muscle fibers parallel to the skin exhibited an increase in reliability. In addition, trained expert operators should be encouraged to use a standardized electrode location and possibly to identify the IZ location prior to positioning. In these conditions, muscle fiber CV estimates (as an important physiological parameter) and slope (as an indicator of muscle fatigue), are suitable for use in sport science, rehabilitation and interventional studies with multisession longitudinal designs. To continuously increase the reporting quality of reliability studies, a critical requirement for future studies is to follow the GRRAS guidelines.

Appendix A

Reliability can be defined as the consistency of a measurement, or more realistically, the amount of measurement error that has been deemed acceptable for the effective practical use of a measurement tool (Atkinson and Nevill, 1998, Bartlett and Frost, 2008). If reliability is high, measurement errors are small in comparison to the true differences between subjects.

In the literature, several terms have been used interchangeably with 'reliability' with varying degree of consistency: 'repeatability', 'reproducibility', 'consistency', 'agreement', 'concordance' and 'stability', although in this systematic review we only considered 'reproducibility' and 'agreement' to be synonyms of reliability. Reproducibility refers to the variation in measurements made on a subject across multiple sessions, whereas agreement quantifies how close two measurements made on the same subject are (Bartlett and Frost, 2008).

There are two types of reliability regarding continuous variables extracted from EMG signals: relative and absolute (Paton and McNamara, 2006). *Relative reliability* is the degree to which individuals maintain their position in a sample with repeated measurements. This type of reliability is usually assessed with some type of correlation coefficient (e.g., intraclass correlation coefficient (ICC) or Pearson's correlation coefficient (r)). *Absolute reliability* is the degree to which repeated measurements vary for an individual, i.e., the lower the variation, the higher the reliability. This type of reliability is expressed either in the actual units of measurement, or as a proportion of the measured value. The standard error of measurement (SEM), coefficient of variation (CoV) and Bland & Altman 95% limits of agreement (LoA) are all examples of measures of absolute reliability. Moreover, the normalized standard error of the mean (nSE) can also be used as an absolute reliability coefficient (Rainoldi et al., 2001). The general advantage of these statistics over indicators of relative reliability is that it is easier to use them, both to extrapolate absolute reliability values to new individuals and to compare the reliability of different measurement tools.

Appendix B

Guidelines for Reporting Reliability and Agreement Studies (GRRAS)-checklist, based on Table I in Kottner et al. (2011)

Section	Item #	Checklist item	Reported on page #
Title/Abstract	1	Identify in title or abstract that interrater/intrarater reliability or agreement was investigated.	
Introduction	2	Name and describe the diagnostic or measurement device of interest explicitly.	
	3	Specify the subject population of interest.	
	4	Specify the rater population of interest (if applicable).	
	5	Describe what is already known about reliability and agreement and provide a rationale for the study (if applicable).	
Methods	6	Explain how the sample size was chosen. State the determined number of raters, subjects/objects, and replicate observations.	
	7	Describe the sampling method.	
	8	Describe the measurement/rating process (e.g. time interval between repeated measurements, availability of clinical information, blinding).	
	9	State whether measurements/ratings were conducted independently.	
	10	Describe the statistical analysis.	
Results	11	State the actual number of raters and subjects/objects which were included and the number of replicate observations which were conducted.	
	12	Describe the sample characteristics of raters and subjects (e.g. training, experience).	
	13	Report estimates of reliability and agreement including measures of statistical uncertainty.	
Discussion	14	Discuss the practical relevance of results.	
Auxiliary material	15	Provide detailed results if possible (e.g. online).	

LIST OF ABBREVIATIONS

AS = anterior scalene; ATM = anterior temporal muscle; BB = biceps brachii; CoV = coefficient of variation; CV = conduction velocity; ICC = intraclass correlation coefficient; IZ = innervation zone; MU = motor unit; PRISMA = Preferred Reporting Items for Systematic Reviews and Meta-Analyses; SCM = sternocleidomastoid; (n)SE = normalized standard error of the mean; SEM = standard error of measurement; sEMG = surface electromyography; TA = tibialis anterior; VL = vastus lateralis ; VMO = vastus medialis obliquus.

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Table 1: Study Characteristics of Included Articles

Authors (y)	Subjects	Muscle	Task	Aims
Linssen et al (1993)	n=26 n=13*	BB	intermittent isometric flexions of the forearm at 80% MVC	To evaluate the inter- and intra-individual repeatability of the muscle fiber CV during fatiguing isometric ischemic intermittent exercise with a contraction rate of 30/min.
Macaluso et al (1994)	n=6	ATM	clenching as hard as possible	To evaluate the behavior of muscle fiber CV and mean power spectrum during fatiguing contractions and to investigate their repeatability.
Merletti et al (1995)	n=6	TA	isometric contractions elicited by electrical stimulation	To investigate test-retest reliability of CV estimates of electrically evoked myoelectric signal shape (M-waves) in isometric conditions.
Hogrel et al (1998)	n=5	VL	isometric knee extensions at 1, 20, 40, 60, 80, 100% MVC	To evaluate reproducibility, sensitivity and variation of CV depending on the electrode location with respect to various contraction modalities.
Merletti et al (1998)	n=9	VM	isometric contractions elicited by electrical stimulation	To investigate test-retest reliability of CV estimates of electrically evoked myoelectric signal shape (M-waves) in isometric conditions.
Harba and Teng (1999)	n=3	BB	isometric flexion of the forearm at 100° joint angle, without weights.	To investigate the reproducibility of measurement of CV from surface EMG using a multi-electrode unit and parallel correlators.
Rainoldi et al (1999)	n=10	BB	isometric flexions of the forearm at 10, 30, 50, 70% MVC	To evaluate the repeatability of estimates and rates of change of muscle fiber CV during voluntary contractions sustained for 30 s at different torque levels.
Rainoldi et al (2001)	n=9	VMO VL	isometric knee extensions at 50% MVC	To evaluate the repeatability of EMG signal muscle fiber CV during voluntary, isometric contractions sustained for 50 s.
Falla et al (2002)	n=9	SCM AS	isometric cervical flexion at 50% MVC	To examine the repeatability and reliability of sEMG-derived indices of muscle fatigue during fatiguing contractions.
Farina et al (2004)	n=10	BB	isometric flexion of the forearm at 50% MVC	To investigate the effect of varying the number of surface EMG signals and the distance between detection points on the standard deviation, sensitivity to electrode displacements over the muscle, and reproducibility of CV estimates.
Ollivier et al (2005)	n=10	BB	isometric flexions of the forearm at 20, 40, 60, 80, 100% MVC	To assess the repeatability of two sEMG recording techniques, the classical bipolar configuration and a Laplacian configuration to assess muscle fiber CV during isometric contractions.

Macdonald et al (2008)	n=20	VL VM	incremental cycling at 20, 40, 60, 80% PPO	To determine the test-retest reliability of muscle fiber CV during incremental and fatiguing cycling using multichannel surface EMG.
McIntosh and Gabriel (2012)	n=40	TA	isometric dorsiflexions of the foot at 30% and 100% MVC	To examine the reliability of CV while using twitch contractions and evoked potentials to orient the surface electrodes with respect to the longitudinal axis of the muscle fibers.
Martinez-Valdes et al (2016)	n=10	VL VM	isometric knee extensions at 10, 30, 50, 70% MVC	To assess the intra-and inter-session reliability of estimates of CV derived from high-density surface EMG.
Beretta-Piccoli et al (2017)	n=40	BB	isometric flexions of the forearm at 20% and 60% MVC	To determine the test-retest reliability of muscle fiber CV obtained from multichannel sEMG recordings.
Martinez-Valdes et (2017)	n=17	VL VM	isometric knee extensions at 10, 30, 50, 70% MVC	To determine the test-retest reliability of motor unit CV extracted from high-density sEMG signals using a novel decomposition approach.
Beretta-Piccoli et al (2018)	n=28	BB	isometric flexions of the forearm at 10, 20, 30, 40, 50, 60, 70, 80, 90% MVC	To evaluate the relationship between force and several EMG variables during isometric contractions and to examine their reliability.

Abbreviations: MVC, maximal voluntary contraction; AS, anterior scalene; ATM, anterior temporal muscle; BB, biceps brachii; CV, conduction velocity; EMG, electromyography; PPO, peak power output; SCM, sternocleidomastoid, VL, vastus lateralis; VM, vastus medialis, VMO, vastus medialis obliquus.

* only 13 subjects participated in the intraindividual reliability analysis.

Table 2: Characteristics of sEMG electrodes and signal acquisition.

Authors (y)	sEMG electrodes				IZ / motor point identification	voluntary contraction	signal type	sEMG signal acquisition		Conduction Velocity	
	type (number)	size (mm)	IED (mm)	location				type	visual channel selection	estimation method	physiological range (m/s)
Linssen et al (1993)	linear array (4)	2	12	anat land	✓	✓	interferential	SD	×	on SD, FFT-based A	NA
Macaluso et al (1994)	linear array (3)	2.75	15	muscle belly	×	✓	interferential	SD	×	on SD, c-c function	NA
Merletti et al (1995)	linear array (4)	10x1	5	anat land	✓	×	single potential	SD	×	on DD, DFT-based AA	2-8
Hogrel et al (1998)	linear array (3)	4	13	anat land	×	✓	interferential	SD	×	on SD, c-c function	NA
Merletti et al (1998)	linear array (4)	10x1	10	anat land	✓	×	single potential	SD	×	on DD, DFT-based AA	2-8
Harba and Teng (1999)	linear array (6)	7.5	7.5, 15	anat land	×	✓	interferential	SD	×	on SD, c-c function	NA
Rainoldi et al (1999)	linear array (4)	4x1	10	anat land	✓	✓	interferential	SD	×	on DD, DFT-based AA	NA
Rainoldi et al (2001)	linear array (4)	4x1	10	anat land	✓	✓	interferential	SD	×	on DD, DFT-based AA	NA
Falla et al (2002)	linear array (4)	5x1	10	anat land	✓	✓	interferential	SD	✓	on DD, DFT-based AA	2.5-6.5 [2]
Farina et al (2004a)	2D array (61)	1.27	5	anat land	✓	✓	interferential	SD	✓	on DD, multichannel maxlike [1]	2-7 [1]
Ollivier et al (2005)	linear array (4) 2D array (11)	4 4	11 10	anat land	✓	✓	interferential	SD	×	on SD, c-c function Laplacian configuration	NA
Macdonald et al (2008)	linear array (4)	7	10	anat land	✓	✓	interferential	SD	×	on DD, multichannel maxlike [3]	2-8
McIntosh and Gabriel (2012)	linear array (3)	10x1	5	anat land	✓	✓	interferential	SD	×	on SD, c-c function	2-10

Martinez-Valdes et al (2016)	2D array (64)	1	8	anat land	✓	✓	single potential	monopolar	✓	on DD, multichannel maxlike [1]	2-6
Beretta-Piccoli et al (2017)	2D array (64)	3	10	anat land	×	✓	interferential	monopolar	✓	on SD, multichannel maxlike [1]	3-8
Martinez-Valdes et (2017)	2D array (64)	1	8	anat land	✓	✓	single potential	monopolar	✓	on DD, multichannel maxlike [1]	2-6
Beretta-Piccoli et al (2018)	2D array (64)	3	10	anat land	×	✓	interferential	monopolar	✓	on SD, multichannel maxlike [1]	3-6.5

Abbreviations: IED, inter-electrode distance; anat land, anatomical landmarks; IZ, innervation zone; SD, single differential; DD, double differential; c-c, cross-correlation; NA, not available; maxlike maximum likelihood; FFT-based, fast Fourier transform based algorithm; DFT-based AA, discrete Fourier transform alignment algorithm.

[1] according to Farina et al., 2001

[2] according to Rainoldi et al., 2001

[3] according to Farina et al., 2004

Table 3: Reliability analysis

STUDY	TEST-RETEST PERIOD	ELECTRODES REPOSITIONING	EXTRACTED PARAMETER	% MVC	MUSCLE	RELATIVE RELIABILITY		ABSOLUTE RELIABILITY			
Macaluso et al (1994)	1 hour	×	ND		ATM	NA					
Hogrel et al (1998)	1 hour	✓, × random	median value	1 20 40 60 80 100	VL	Reliability of the median estimate was assessed by verifying that its 95% confidence interval was within the limits of the system resolution					
			slope	80		good test-retest reliability					
Martinez-Valdes et al (2016)					VL	test-retest ICC	inter ICC	CoV (%) test-retest	CoV (%) inter	SEM test-retest	SEM inter
	T1-T2: 15’ T2-T3: 30’ T1-T3: 45’	×	mean value	10		0.89	0.85	1.5	2.0	0.07	0.09
				30		0.85	0.86	1.7	1.8	0.09	0.09
				50		0.92	0.92	1.8	1.8	0.1	0.1
				70		0.93	0.97	1.6	1.7	0.11	0.09

				10	VM	0.94	0.95	1.3	1.3	0.07	0.06
				30		0.88	0.91	1.9	1.6	0.09	0.09
				50		0.95	0.96	1.5	1.4	0.09	0.08
				70		0.97	0.94	1.5	1.6	0.09	0.11
	1 week	✓ the skin was marked									
Beretta-Piccoli et al (2018)						test-retest ICC	inter ICC				
				10		0.95	0.79				
	1 hour	×		20		0.97	0.76				
				30		0.98	0.77				
			initial value	40	BB	0.97	0.68				
				50		0.96	0.39				
				60		0.96	0.59				
				70		0.90	0.21				
				80		0.91	0.04				
				90		0.96	0.22				
	1 week	✓									
Merletti et al (1995)	T1-T2: 12’ T2-T3: 20’	✓ the skin was marked	initial value	ES	TA	ICC 0.11	Pearson’s r 0.25; 0.12; 0.26				

	T1-T3: 32’		n slope			0.44	0.45; 0.88; 0.62		
			area ratio			0.44	0.47; 0.82; 0.56		
Merletti et al (1998)						ICC	Pearson’s r	CoV (range)	
			initial value			0.36	0.83	9.1 (5.1-12)	
							0.88		
							0.70		
	T1-T2: 4’ T2-T3: 4’ T1-T3: 8’	✓ the skin was marked	n slope	ES	VM	0.42	0.41 0.89 0.35	49.5 (16-82)	
			area ratio			0.43	0.68	44.9 (23-76)	
							0.94		
							0.60		
Harba and Teng (1999)	few seconds	✓	initial value	ND	BB			relative variance R (squared CoV) 5.4%	
Linssen et al (1993)	1 week	✓	initial value	80	BB	Pearson’s r = 0.81		SE = 0.37	
			slope			Pearson’s r = 0.80		SE = 0.62	
Rainoldi et al (1999)	3 consecutive	✓			BB	ICC		(n)SE within (%)	(n)SE between (%)

	days	the skin was marked	initial value	10		0.40	1.88	2.21
				30		0.26	2.52	2.47
				50		-0.22	3.09	1.50
				70		-0.27	3.15	1.10
			slope	10		-0.05		
				30		0.03		
				50		0.14		
				70		0.30		
Rainoldi et al (2001)						ICC	Fisher test F ratio	(n)SE within (%)	(n)SE between (%)
	3 consecutive days	✓ the skin was marked	initial value		r VL	0.80	12.44	4.60	9.39
					r VMO	-0.10	0.63	7.96	5.38
					l VL	0.40	2.61	5.57	5.19
				50	l VMO	-0.08	0.76	5.99	5.21
			slope		r VL		0.83		
					r VMO		0.58		
					l VL		0.12		
					l VMO		1.15		

n slope	r VL	0.83
	r VMO	1.01
	l VL	0.25
	l VMO	1.49

Abbreviations: MVC, maximal voluntary contraction; AS, anterior scalene; ATM, anterior temporal muscle; BB, biceps brachii; SCM, sternocleidomastoid, VL, vastus lateralis; VM, vastus medialis, VMO, vastus medialis obliquus; NA, not available; ND, not defined; ICC, intraclass correlation coefficient; MU, motor unit; n slope, normalized slope; (n)SE, (normalized) standard error of the mean; (n)SEM, (normalized) standard error of measurement; CoV, coefficient of variation; LofA, level of agreement; B&A, Bland and Altman; MDC95, minimal detectable change; T1, trial 1; ES, electrical stimulation; intra, intrasession; inter, intersession.

** see text for explanations.

Captions to illustrations

Figure 1 : PRISMA Flowchart of study retrieval, screening and eligibility

Figure 2: Stacked bar chart representing reliability reporting quality of the reviewed studies (n=17)

Figure 1

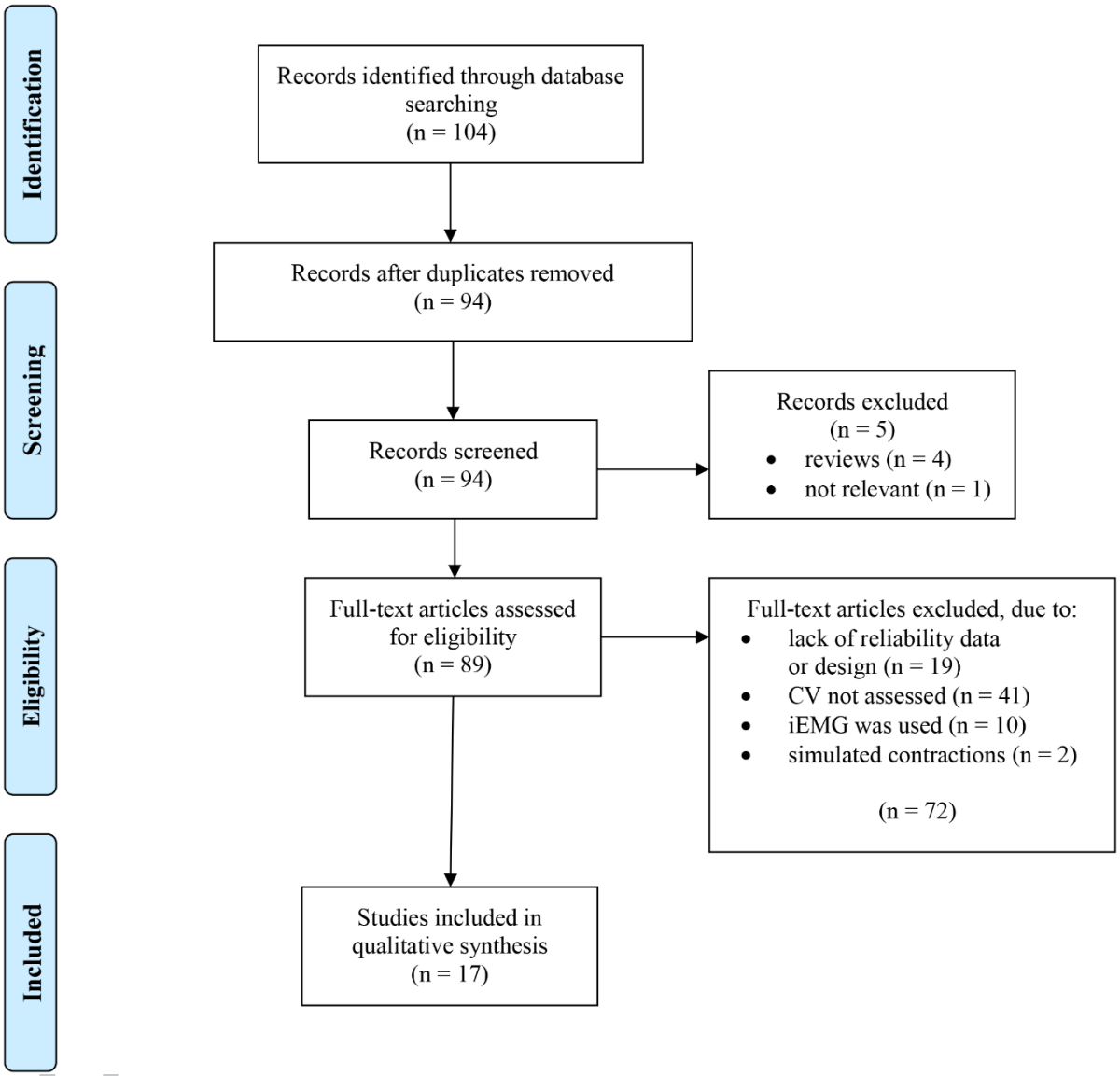
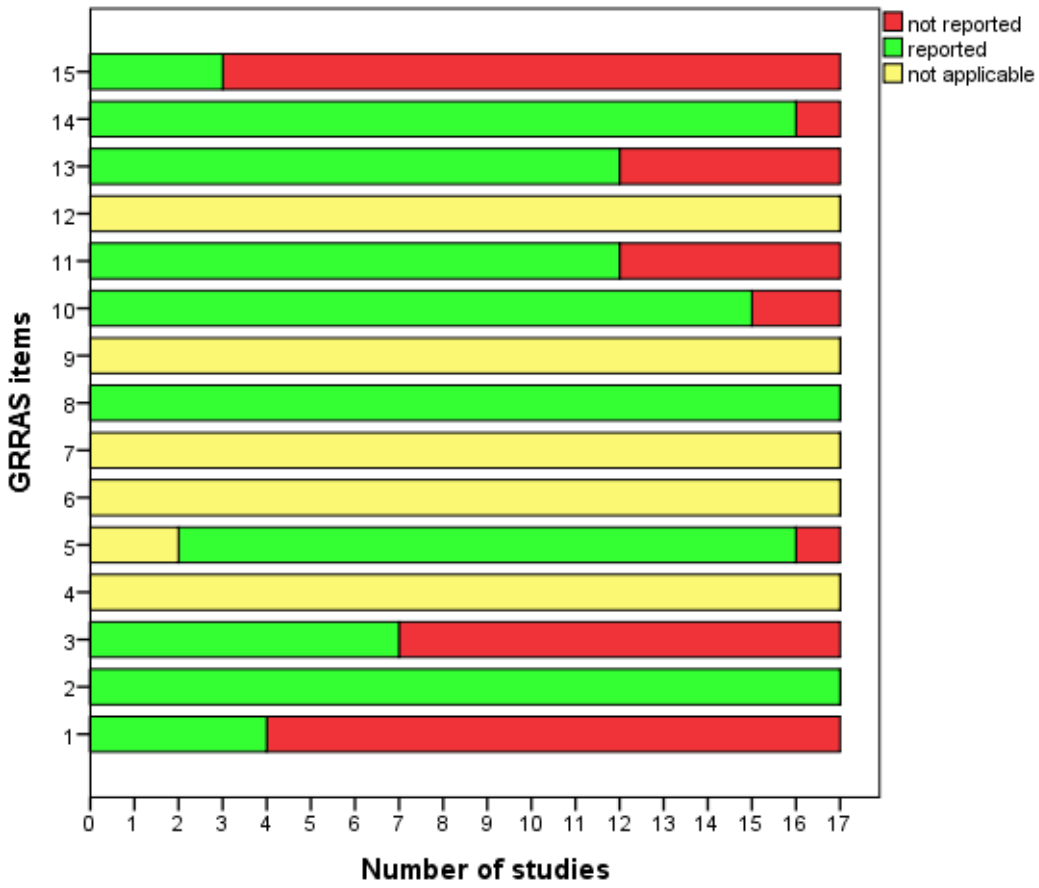


Figure 2



AUTHOR BIOGRAPHY

Matteo Beretta-Piccoli received his MSc. in 2003 from the University of Milan in Biological Sciences. Since 2006 he is teacher of neurophysiology in the Bachelor courses of physiotherapy and occupational therapy at the University of Applied Sciences and Arts of Southern Switzerland. Since 2008 he is also researcher at the Rehabilitation Research Laboratory 2rLab. In 2017 he started a PhD program in Biomedical Sciences at the University of Pavia. His current research interests include motor fatigability in neurological disorders and muscle physiology.

Corrado Cescon received his PhD in Biomedical Engineering at Politecnico di Torino, he was a fellow of the Laboratory for Engineering of the Neuromuscular System (LISiN) for twelve years. In 2007 he was Research Assistant Professor at the Center for Sensory Motor Interaction, Aalborg University, Denmark. Since 2011 he is a senior researcher at University of Applied Sciences and Arts of Southern Switzerland, Manno, Switzerland. His main interests are the design of algorithms, the processing of biomedical signals and kinematics. He was also involved in the design of rectal probes, development of algorithms for innervation zone identification from multichannel sEMG recordings and design and development of electronic devices for biofeedback and muscle-based generation of music.

Marco Barbero is Professor in Physiotherapy at the University of Applied Sciences and Arts of Southern Switzerland. He is currently head of the Rehabilitation Research Laboratory 2rLab at the Department of Business Economics, Health and Social Care. He received his Physical Therapy degree in 1999 from the University of Milan, Italy. He obtained a master's

degree in musculoskeletal rehabilitation at University of Genoa in 2005, and in 2016 earned his PhD at the at Queen Margaret University in Edinburgh. His research involves the integration of neurophysiological and clinical research to improve the treatment of musculoskeletal pain.

Giuseppe D'Antona, MD is Professor in Physiology at the Faculty of Medicine and Surgery at the University of Pavia (Italy) and Director of the CRIAMS Sport Medicine Center in Voghera. He received his PhD in Physiology in 2002 from the same University. His research interests are focused on contractile and biochemical parameters of muscle function in sarcopenia of ageing and muscular dystrophy. Moreover, he is interested in the identification of strategies for sport therapy and nutritional supplementation in rare diseases and, in particular, in muscular dystrophies.