Consensus for experimental design in electromyography (CEDE) project

Besomi, Manuela; Devecchi, Valter; Falla, Deborah; McGill, Kevin; Kiernan, Matthew C.; Merletti, Roberto; van Dieën, Jaap H.; Tucker, Kylie; Clancy, Edward A.; Søgaard, Karen; Hug, François; Carson, Richard G.; Perreault, Eric; Gandevia, Simon; Besier, Thor; Rothwell, John C.; Enoka, Roger M.; Holobar, Aleš; Disselhorst-Klug, Catherine; Wrigley, Tim

DOI:
10.1016/j.jelekin.2024.102874

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Besomi, M, Devecchi, V, Falla, D, McGill, K, Kiernan, MC, Merletti, R, van Dieën, JH, Tucker, K, Clancy, EA, Søgaard, K, Hug, F, Carson, RG, Perreault, E, Gandevia, S, Besier, T, Rothwell, JC, Enoka, RM, Holobar, A, Disselhorst-Klug, C, Wrigley, T, Lowery, M, Farina, D & Hodges, PW 2024, 'Consensus for experimental design in electromyography (CEDE) project: Checklist for reporting and critically appraising studies using EMG (CEDE-Check)', *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology*, vol. 76, 102874. https://doi.org/10.1016/j.jelekin.2024.102874

Journal of Electromyography and Kinesiology 76 (2024) 102874

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Consensus for experimental design in electromyography (CEDE) project: Checklist for reporting and critically appraising studies using EMG (CEDE-Check)

Manuela Besomi [a], Valter Devecchi [b], Deborah Falla [b], Kevin McGill [c], Matthew C. Kiernan [d,e], Roberto Merletti [f], Jaap H. van Dieën [g], Kylie Tucker [a,h], Edward A. Clancy [i], Karen Søgaard [j], François Hug [h,k,l], Richard G. Carson [m,n,o], Eric Perreault [p,q], Simon Gandevia [r], Thor Besier [s], John C. Rothwell [t], Roger M. Enoka [u], Aleš Holobar [v], Catherine Disselhorst-Klug [w], Tim Wrigley [x], Madeleine Lowery [y], Dario Farina [z], Paul W. Hodges [a,*]

[a] School of Health and Rehabilitation Sciences, The University of Queensland, Brisbane, Australia
[b] Centre of Precision Rehabilitation for Spinal Pain (CPR Spine), School of Sport, Exercise and Rehabilitation Sciences, University of Birmingham, UK
[c] US Department of Veterans Affairs, United States
[d] Brain and Mind Centre, University of Sydney, Sydney, Australia
[e] Department of Neurology, Royal Prince Alfred Hospital, Sydney, Australia
[f] LISiN, Department of Electronics and Telecommunications, Politecnico di Torino, Torino, Italy
[g] Department of Human Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam Movement Sciences, Amsterdam, Netherlands
[h] School of Biomedical Sciences, The University of Queensland, Brisbane, Australia
[i] Worcester Polytechnic Institute, Worcester, MA, USA
[j] Department of Clinical Research and Department of Sports Sciences and Clinical Biomechanics, University of Southern Denmark, Odense, Denmark
[k] LAMHESS, Université Côte d'Azur, Nice, France
[l] Institut Universitaire de France (IUF), Paris, France
[m] Trinity College Institute of Neuroscience and School of Psychology, Trinity College Dublin, Dublin, Ireland
[n] School of Psychology, Queen's University Belfast, Belfast, UK
[o] School of Human Movement and Nutrition Sciences, The University of Queensland, Brisbane, Australia
[p] Northwestern University, Evanston, IL, USA
[q] Shirley Ryan AbilityLab, Chicago, IL, USA
[r] Neuroscience Research Australia, University of New South Wales, Sydney, Australia
[s] Auckland Bioengineering Institute and Department of Engineering Science, University of Auckland, Auckland, New Zealand
[t] Sobell Department of Motor Neuroscience and Movement Disorders, UCL Institute of Neurology, London, UK
[u] Department of Integrative Physiology, University of Colorado Boulder, CO, USA
[v] Faculty of Electrical Engineering and Computer Science, University of Maribor, Koroška cesta 46, Maribor, Slovenia
[w] Department of Rehabilitation and Prevention Engineering, Institute of Applied Medical Engineering, RWTH Aachen University, Aachen, Germany
[x] Centre for Health, Exercise and Sports Medicine, Department of Physiotherapy, University of Melbourne, Parkville, Australia
[y] School of Electrical and Electronic Engineering, University College Dublin, Belfield, Dublin, Ireland
[z] Department of Bioengineering, Imperial College London, London, UK

A B S T R A C T

The diversity in electromyography (EMG) techniques and their reporting present significant challenges across multiple disciplines in research and clinical practice, where EMG is commonly used. To address these challenges and augment the reproducibility and interpretation of studies using EMG, the Consensus for Experimental Design in Electromyography (CEDE) project has developed a checklist (CEDE-Check) to assist researchers to thoroughly report their EMG methodologies. Development involved a multi-stage Delphi process with seventeen EMG experts from various disciplines. After two rounds, consensus was achieved. The final CEDE-Check consists of forty items that address four critical areas that demand precise reporting when EMG is employed: the task investigated, electrode placement, recording electrode characteristics, and acquisition and pre-processing of EMG signals. This checklist aims to guide researchers to accurately report and critically appraise EMG studies, thereby promoting a standardised critical evaluation, and greater scientific rigor in research that uses EMG signals. This approach not only aims to facilitate interpretation of study results and comparisons between studies, but it is also expected to contribute to advancing research quality and facilitate clinical and other practical applications of knowledge generated through the use of EMG.

* Corresponding author at: School of Health and Rehabilitation Sciences, The University of Queensland, Brisbane, Qld 4072, Australia.
E-mail address: p.hodges@uq.edu.au (P.W. Hodges).

https://doi.org/10.1016/j.jelekin.2024.102874

Available online 13 March 2024

1. Introduction

The quality and reporting of electromyography (EMG) can impact the utility and confidence of findings across multiple research and clinical disciplines, including neurology, neuroscience, physiology, sports science, and rehabilitation. Incomplete reporting might limit interpretation and replication, contribute to unexplained heterogeneity in *meta*-analyses, and impede the translation of research into clinical practice. As such, there is a need to advocate for best practices in EMG application and standardised reporting of EMG methodology, to enhance scientific rigor across studies.

Several factors related to the EMG recording process can adversely influence the results. For example, joint angles, angular velocities, and type of muscle contractions can influence EMG signals. Failure to control these factors can introduce variability and bias findings across studies (Farina et al., 2001; Madeleine et al., 2001). Similarly, the procedure for placement of EMG electrodes on participants, the specific type of electrodes chosen, and the protocols for acquiring EMG signals are all important details that, if not clearly reported, can further confound study interpretation and replication efforts (Campanini et al., 2007; Castroflorio et al., 2005; Clancy et al., 2002; Farina et al., 2002).

The "Consensus for Experimental Design in Electromyography (CEDE) project" has published a series of matrices to promote evidence-based best practice in the application of EMG techniques (Besomi et al., 2020; Besomi et al., 2019; Gallina et al., 2022; Martinez-Valdes et al., 2023; McManus et al., 2021). These matrices provide recommendations and explanations to inform for selection of the most appropriate EMG methodology to match the specific purpose of research or clinical application of EMG. This paper draws on that work to present a comprehensive checklist that addresses key methodological areas that require careful consideration when planning and reporting studies involving the use of EMG to best ensure the accuracy and reproducibility of the results.

The checklist is designed to be used alongside other appropriate checklists, such as CONSORT for randomised trials (Schulz et al., 2010) and STROBE for observational studies (von Elm et al., 2007) to help ensure that the research reporting process is robust. A multi-stage Delphi process, coordinated by experts in the application and reporting of EMG from various disciplines, was used to reach a consensus on the items that should be reported in studies using EMG. The primary goal of this work was to create a checklist that would encourage researchers provide a thorough report on the details of the EMG methods. The format of the checklist and supporting material encourages critical thinking regarding the rationale behind their chosen methods, and whenever possible, supports researchers to understand and utilize best practices. This checklist also serves as a resource for reviewers, editors, and other users of research for the critical appraisal and evaluation of EMG studies. By encouraging its widespread adoption, we aim to promote standardization, transparency, and rigor in EMG research, with the goal of advancing research quality and practical (e.g., clinical) impact.

2. Methods

The method used for the development of this checklist followed a process similar to that employed in previous CEDE matrices (Besomi et al., 2020; Besomi et al., 2019; Gallina et al., 2022; Martinez-Valdes et al., 2023; McManus et al., 2021) and described in detail elsewhere (Hodges, 2020). We followed a three-step process: 1) initial listing and rating of potential items via an online survey; 2) development of the checklist draft; 3) Delphi process for consensus. The steering committee, composed of four CEDE members (DF, MK, KM, RM), and two early career researchers (MB & VD), led the development of this checklist. All those who participated in the online survey and Delphi process are listed as co-authors. The Human Research Ethics Committee of The University of Queensland, Australia approved this project.

2.1. Online survey

An online survey was sent to all 17 contributors to gather an initial list of potential items that could be included in the checklist (Appendix 1). We divided the items (73 in total) into five categories: 1) participant factors, 2) study design, 3) task, 4) methodological factors, and 5) outcome(s) of interest or feature(s) extracted from EMG signals. Contributors were asked to report whether they would include, remove, or were unsure about the inclusion/exclusion of each item, and were able to suggest new items.

2.2. Development of the draft

The draft of the EMG checklist was developed by the steering committee based on the responses to the online survey. A list of the items included in the first round of the Delphi process is presented in Appendix 2. We considered "Essential" items to be those that always should be reported in EMG studies, and "If applicable" items those that might be applicable depending on the study design, research question, aim(s), and methods. We divided the items that were considered "include" or "unsure" ($n = 54$) into four categories: 1) study design (4 essential items), 2) participant characteristics (3 essential items, 4 if applicable items), 3) task (3 essential items, 7 if applicable items), and 4) procedure for EMG recording: electrode placement (4 essential items, 5 if applicable items), characteristics of recording electrodes (all essential items and divided based on electrode type), and acquisition of EMG signals (7 essential items, 5 if applicable items).

2.3. Delphi process

The Delphi process is a widely accepted method to achieve consensus (Waggoner, Carline and Durning, 2016). The approach used in the current matrix was similar to the one employed in previous CEDE projects and is described in detail elsewhere (Hodges, 2020). The aim of the questionnaire was to gain consensus regarding the essential criteria for a checklist that would enable critical appraisal and systematic reporting of EMG studies. The steering committee oversaw the project and integrated comments but did not participate in the Delphi process. The Delphi questionnaires were sent online using a centrally supported survey tool (Checkbox Survey Software; https://www.checkbox.com) from The University of Queensland. Contributors were asked to indicate their opinion regarding whether an item should be included in the checklist when reporting EMG studies. A five-point Likert scale was provided with the following options: "unsure", "never", "some of the time", "most of the time", and "always" in ascending order. Consensus for included items was defined as 70 % or more of the respondents indicating that an item should be reported 'most of the time' or 'always'; fewer than 15 % scoring it as 'unsure' or 'never'; and an interquartile range < 2 points. A free-text box was provided to add any comments or suggestions. Fig. 1 illustrates the stages of the Delphi process. This study adheres to the Conducting and Reporting Delphi Studies (CREDES) recommendations (Jünger et al., 2017) (Appendix 3).

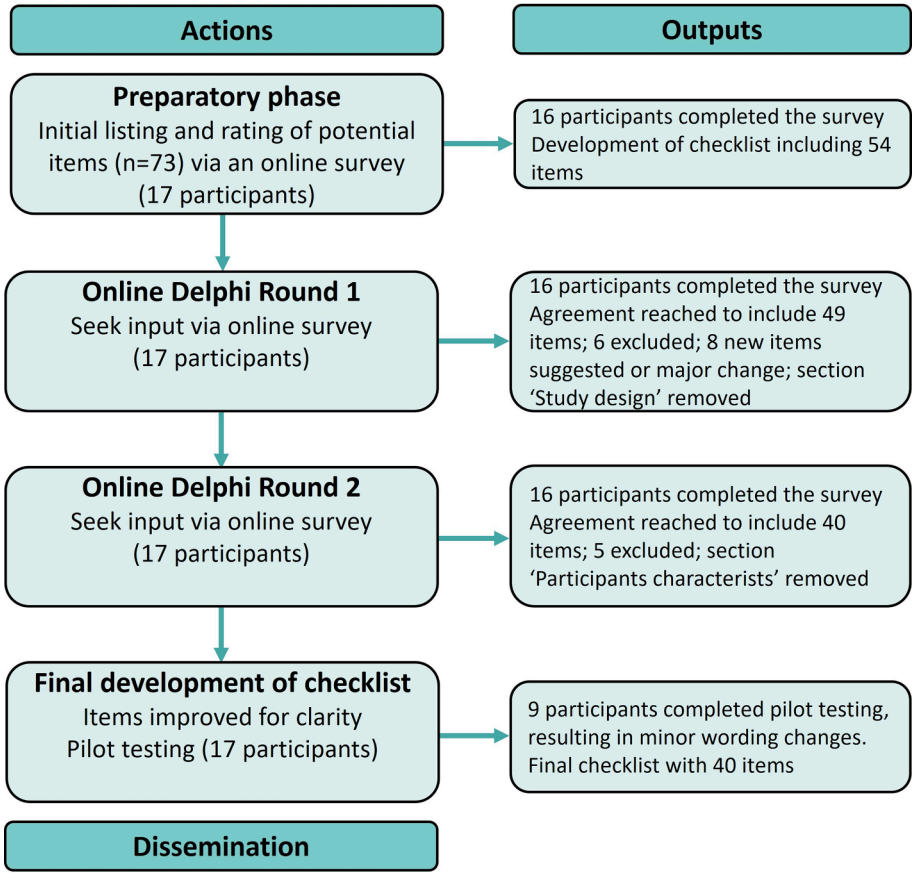

Fig. 1. Flowchart with stages of the Delphi process.

3. Results

From the 17 experts who agreed to participate in the Delphi process, 16 (94 %) replied to the first-round questionnaire. Version 1 (Appendix 2) comprised 54 items. After round one, six items were removed due to a low consensus among the experts, the "Task(s)" section was substantially modified based on feedback, and the "Study design" section was removed after feedback and agreement with the steering committee because it was not EMG specific and was redundant given the inclusion of these items in other established checklists, e.g. STROBE and CONSORT (Schulz et al., 2010; von Elm et al., 2007). A total of 49 items were then included in the second-round questionnaire, which was resubmitted to the 17 original experts. Compared with round one, eight items were added or received major changes based on comments during the first round and discussion with the steering committee. The same sixteen experts (94 %) completed the second-round questionnaire (Appendix 4). After round two, five items were removed due to a low consensus and the section "Participants characteristics" was removed after feedback and agreement with the steering committee. A total of 40 items were included in the final version. A summary of the results of the Delphi consensus process is presented in Appendix 5. A few additional amendments were made to the checklist after a pilot test assessment. At this stage, the same 17 experts who contributed to the Delphi process evaluated one article, randomly selected from a set of four EMG studies, using the developed checklist. Nine experts were able to test the checklist and provided their feedback of the process. Item 13 was slightly modified, and the column "Comments" was added to the checklist to clarify why or if an item was not reported or only partially reported. The final CEDE checklist (CEDE-Check) endorsed by the CEDE project team is presented in Table 1 and can be downloaded here.

4. Discussion

The aim of this study was to design a checklist to guide the use of EMG methodology and promote standardisation in the reporting of studies conducted in humans that use EMG. The CEDE team developed the final EMG methodological checklist (CEDE-Check) through an online survey using the Delphi technique. CEDE-Check comprises 40 items: 10 related to the task of interest and 30 to the procedure of EMG recording (i.e., electrode placement, characteristics of recording electrodes, and acquisition of EMG signals and pre-processing). The intention is that the checklist be used by researchers when planning the design of their experiments - with the aim of ensuring that the necessary methodological and analytical procedures are followed, by scholars appraising studies in which EMG has been used, and by reviewers, editors, and readers - assisting in the evaluation and interpretation of findings.

4.1. Rationale for checklist development

There was a clear need for a standardized checklist for reporting and critically appraising EMG studies. EMG is a valuable technique used to assess muscle activity in biomedical research and clinical practice (Basmajian & De Luca, 1985). However, the lack of standardized reporting makes it challenging to compare and replicate studies. The absence of specific guidelines impedes researchers, clinicians, and reviewers, who may wish to understand the critical elements of a piece of EMG research, such as methods of data collection, analysis, and interpretation. This is particularly important given the presence of wide variation in EMG recording and analysis techniques, that without due consideration, can influence the interpretation of research findings.

Table 1
CEDE Research Checklist for reporting and critically appraising studies using EMG (CEDE-Check).

Section/topic	Item	Description
Task(s)		
	1	Context of research (e.g., laboratory, clinical setting, sport setting, daily-life environment)
	2	Description of task(s) with sufficient detail for replication, should include description of the adopted set-up (e.g., start/end position, joint angles, body posture, or any other potential constraint) and equipment (if any)
	3	Specify type of contraction (e.g., isometric, dynamic, concentric, eccentric) of the recorded muscle(s)
	4	Specify duration/number of repetitions, recovery/rest period between repetitions/tasks, and speed of movement/contraction (or whether speed was defined by instructions like "self-paced", "as fast as possible" or by a specific devices like treadmill, metronome, isokinetic machine)
	5	Specify if part of the task/repetition(s)/trials(s) were not recorded or excluded, with justification for the removal of data.
	6	Description of warm-up/familiarisation
	7	Instructions given to the participant on how the task should be performed (e.g., "as fast as possible" or "as accurately as possible")
	8	When two or more tasks are performed, specify order or method of randomisation/counterbalancing
	9	If graded submaximal contractions are performed, specify how intensity was controlled (e.g., visual feedback from a screen), percentage of maximal voluntary contraction (MVC), instructions used, and how the MVC was assessed and calculated. Please refer to "CEDE Amplitude normalisation matrix"(Besomi et al., 2020)
	10	Description of task(s) performed for amplitude normalisation. Please refer to "CEDE Amplitude normalisation matrix" (Besomi et al., 2020)
Procedure for EMG recording		
a) **Electrode placement**	11	Muscle(s) investigated and side of body
	12	Electrode type (e.g., conventional surface electrode, array or grid of electrodes, fine-wire electrode, needle electrode). Please refer to the "CEDE Electrode selection matrix" (Besomi et al., 2019)
	13	Procedure for skin preparation (both for surface and intramuscular electrodes). Describe steps of the procedure (e.g., shaving of hair, scrubbing of skin, antibacterial skin preparation) and products used (e.g., abrasive paste including manufacturer).
	14	Description of electrode placement with sufficient detail for replication and reference to guidelines as appropriate (e.g., SENIAM, CEDE (Alessio Gallina et al., 2022; Besomi et al., 2020; Besomi et al., 2019; Martinez-Valdes et al., 2023; McManus L et al., 2021), Journal of Electromyography and Kinesiology tutorials (Clancy et al., 2023; A. Del Vecchio et al., 2020; Merletti & Cerone, 2020; Merletti & Muceli, 2019)). Provide details on the adopted methods to ensure appropriate electrode placement and orientation with respect to muscle fascicle direction (e.g., along muscle fibres, distance from anatomical landmarks, ultrasound guided) depending on study aim and feasibility for the investigated muscle. If electrode placement differs from guidelines, specify why, and describe in detail.
	15	Positioning of reference electrode(s)
	16	If multiple sessions are performed with the intention to record from a similar region of a muscle, describe the methods adopted to ensure consistency of electrode placement
b) **Characteristics of recording electrodes**	*Surface electrodes (including reference electrode(s))*	
	17	Physical configuration (e.g., concentric, bipolar, array, grid)
	18	Electrode size (e.g., diameter of recording area of the electrode, length), material (e.g., Ag/AgCl), and shape (e.g., circular, bar). If determined by a company/manufacturer, report this from the information provided.
	19	Interelectrode distance (specify center to center, or edge to edge). If determined by a company/manufacturer, report this from the information provided.
	20	Number of electrodes (if electrode grid was used, specify the number of rows and columns, and missing electrode(s) if any)
	21	Electrode type (wet, dry, insulating), model and company (if appropriate), characteristics of the electrode skin contact (e.g., double adhesive foam, adhesive tape, Velcro belt, use of conductive paste or gel) and electrode fixation.
	Fine wire intramuscular electrodes	
	22	Recording montage (e.g., bipolar, monopolar, others)
	23	Wire type and properties (e.g., diameter, wire, and insulation material, single or multistrand, characteristics of the conductive wire, method for insulation removal)
	24	Approximate length of exposed conductor and bent tips. If determined by a company/manufacturer, report this from the information provided.
	25	For a bipolar pair: separation between electrodes and how this was controlled (glued pair, staggered pair, monopolar with respect to a surface reference). If determined by a company/manufacturer, report this from the information provided.
	26	Size (diameter and length) of the needle used for insertion, orientation during insertion and fine wire fixation technique (if any)
	Needle intramuscular electrodes	
	27	Type of needle (e.g., monopolar, concentric, bipolar, quadrifilar, tungsten) including brand
	28	Needle size (gauge), length, and type of metal contact (e.g., stainless steel)
	29	Describe the orientation during insertion
c) **Acquisition of EMG signals and pre-processing**	30	Detection mode of EMG signals (e.g., monopolar, single differential, double differential, etc)
	31	Brand and model of the EMG acquisition system, or report details (i.e., input impedance, equivalent input voltage noise, bandwidth, common mode rejection ratio) if custom-built.
	32	Gain of amplifier and cut-off frequencies of hardware filter (and if possible, filter type and order). If determined by a company/manufacturer, report this from the information provided.
	33	Sampling frequency (Hertz or samples/s). If determined by a company/manufacturer, report this from the information provided.
	34	Analog-to-digital (A/D) resolution (bits) and full range (without risk of saturation). If determined by a company/manufacturer, report this from the information provided.
	35	Name and version of the software used to record the EMG signals or specify if custom-made.
	36	Technique(s) applied for power line interference removal (none, driven right leg (DRL), notch filter(s), frequency interpolation, others), including the relevant features (width of band reject, filter order, number of power line interference harmonics removed, etc.)
	37	Acquisition/synchronisation with other devices (when distinct channels are not automatically synchronized. e.g., force, movement capture). Report any inherent delay (if any) induced by the recording system, and how it was compensated for.
	38	If wireless, specify method of transmission (e.g., Bluetooth, Radiofrequency)
	39	If wearable system was used, specify the dimension, weight, fixation method, and transmission range. If determined by a company/manufacturer, report this from the information provided.
	40	Pre-amplification of signal and location relative to the electrode (if used)

Download CEDE-Check

The existing reporting practices in EMG research, such as the European Project "Surface Electromyography for Non-Invasive Assessment of Muscles" (SENIAM) guidelines (Hermens et al., 1999) and the standards for reporting EMG data (Merletti, 1999) have improved the quality of reporting, but there are some limitations. These guidelines provide "standards" for EMG practice that may not align with all experimental designs and recording procedures, especially considering they were proposed over 20 years ago before significant technological advancements in the field. Standardization of EMG techniques is difficult to implement partly due to the continuous developments in techniques, including novel sensors for EMG recording (Murciego et al., 2023; Myers et al., 2014) and innovative processing methods (Farina et al., 2014; Herak & Zubčević, 2022; Martinek et al., 2021). Finally, the SENIAM guidelines pertain only to isometric contractions, and they are not up to date with contemporary approaches. We used a Delphi technique, a valuable method for developing consensus-based checklists in various fields, including healthcare, research, and industry (von der Gracht, 2012; Waggoner et al., 2016). It has several advantages, including participant anonymity, geographic diversity, flexibility, and an iterative process (von der Gracht, 2012).

4.2. Development process of the CEDE-Check

Several items were excluded after the Delphi process. Based on feedback from the first round, a few items were added and tested in the second round. The entire section relating to study design and participant characteristics was removed. Although these items are important and should be reported, we considered them not specific to EMG research. We recommend that researchers also use other standard guidelines and checklists, such as STROBE (von Elm et al., 2007) and CONSORT (Schulz et al., 2010), to guide the reporting of general study design features and participant information. The CEDE-Check provides a list of items that should be reported, and this requires consideration of the task of interest and procedures used to acquire EMG recordings. The framework does not provide guidance on how to perform the selected methods or how the data should be analysed. Instead, we suggest that researchers use the available recommendations from the CEDE team (Besomi et al., 2020; Besomi et al., 2019; Gallina et al., 2022; Martinez-Valdes et al., 2023; McManus et al., 2021) and tutorials published by the Journal of Electromyography and Kinesiology (Clancy et al., 2023; A Del Vecchio et al., 2020; Merletti & Cerone, 2020; Merletti & Muceli, 2019; Staudenmann et al., 2010) to guide decision-making in relation to the use of specific methods.

As a further step in the development process, we asked the CEDE members who contributed to the Delphi process to test the checklist. This step allowed us to test the functionality of the checklist and make final refinements when these were needed to ensure the checklist's effectiveness and usability. Only minor changes to wording were suggested, which did not alter the consensus process. Future studies will assess the inter- and intra-rater reliability of the checklist. The checklist is intended to be a living document that is updated as new information becomes available, or research practices evolve.

4.3. Utility and adoption of the CEDE-Check

This checklist is expected to aid in the critical appraisal of studies, especially when comparing papers that address a similar research question. This uniform approach may be of value when conducting topical reviews or *meta*-analyses. Depending on the study design, items from the checklist that should be reported can be used to determine whether the results of a study were potentially confounded by methodological factors that may have impacted EMG measures. It is important to note that the specific set of factors that should be reported will depend on the hypotheses and aims. Thus, issues that are crucial for one investigation may be less important for others and, therefore, the hypotheses and aims of a study need to be considered when using the CEDE-Check to evaluate the methodology.

We have developed the CEDE-Check as a comprehensive checklist for reporting EMG methodologies in human studies, encompassing both adults and children, in both health and disease. The items included in the checklist are relevant and applicable to any population, including children. Additionally, the checklist allows for flexibility, enabling researchers to disregard an item when it is not applicable. We acknowledge the importance of addressing specific research issues that may arise in children's studies, and we encourage researchers to utilize the CEDE-Check in conjunction with other checklists to ensure a comprehensive approach to reporting EMG methodologies.

Similarly, the recommendations and CEDE-Check apply across EMG applications, including laryngeal and urogenital studies (Keshwani & McLean, 2015; Merletti, 2016; Stafford et al., 2010; Varadarajan et al., 2013), as well as EMG-driven robotic studies (Cisnal et al., 2021; Hu et al., 2009). Consistent with previous CEDE matrices (Besomi et al., 2019), the same considerations apply in reporting electrode locations with respect to anatomical references and the electrode geometry when it differs from conventional surface electrodes (e.g., cylindrical probes used to study surface EMG of the anal sphincter or vaginal muscles). The research applications of surface EMG exceed those mentioned in other CEDE papers, which are not exhaustive. Specific applications may need additional considerations; for example, underwater surface EMG requires means to prevent water from creating conductive bridges between electrodes.

4.4. Impact on reporting quality

It is not unknown for researchers to provide incomplete information concerning key aspects of their EMG studies, such as electrode placement, signal processing techniques, and data analysis methods. This practice may make it difficult for others to evaluate the reliability and validity of the results. Rigorous scientific research and the advancement of knowledge relies on the reproducibility of findings. The potential to replicate depends on the availability of a detailed and standardised description of the original methodology. The practice of referring to a methodology without detailed explanation, such as simply stating "electrodes placed according to SENIAM", is therefore not recommended. It is instead essential to provide a comprehensive and clear description of the methodology that has been used.

Inconsistencies in reporting across studies also hinder the establishment of best practices in the field. By emphasizing the importance of specific aspects of EMG research, such as electrode positioning, data preprocessing, and statistical reporting, checklists encourage researchers to follow guidelines and adopt best practices. Such an approach promotes consistency in methodology and reporting, making it easier for the scientific community to build on previous work and advance the field (Eby et al., 2020).

4.5. Challenges and limitations

The use of checklists in research, although valuable for promoting consistency and reducing errors, can still be susceptible to bias or subjectivity. Some potential sources of bias or subjectivity include but are not limited to, selection, interpretation, and contextual biases. If the checklist is not designed to be comprehensive or if certain items are omitted, it can introduce selection bias. This means that researchers may focus on specific aspects while neglecting others, leading to an incomplete or biased assessment of the research.

In this regard, the extensive use of EMG across varied research fields represented a unique challenge in the development of a comprehensive checklist for EMG reporting. Our objective was to develop a checklist

that was both succinct and comprehensive, ensuring it was practical while thorough in its coverage of key factors affecting EMG recording across different fields. Additionally, we aimed to use of clear, technically precise terminology, differentiating between essential requirements applicable to all EMG studies (i.e., essential items) and those specific to distinct research objectives or methods (i.e., "if applicable" items). These challenges were accommodated with our multi-stage Delphi process led by EMG experts from different disciplines. Previous outputs from the CEDE project have promoted the consistent use of terminology and provided additional guidance for users of the CEDE-Check. When submitting a manuscript, authors can explicitly indicate in the methodology section which elements they have reported and, if they have not, justify the reasons and discuss the potential impact and limitations of the findings. However, some specific factors not covered by the checklist may be deemed necessary based on the specific aims and nuances of the study.

There can be differences in the interpretation of checklist items among researchers, which can lead to subjectivity in the assessment of whether the criteria have or have not been met. Our first test and validation process were designed to mitigate this potential interpretation bias. Additionally, the context in which the checklist is used can influence its application. For example, the same research may be assessed differently if it is conducted in a clinical setting versus a laboratory, leading to context-specific bias. To mitigate these sources of bias and subjectivity, it is essential to have clear and transparent guidelines for checklist usage, provide training to checklist users, use multiple reviewers for consensus, and periodically update the checklist to incorporate emerging evidence and best practices. The CEDE team will endeavour to develop and refine mechanisms to disseminate this work and provide training if necessary (e.g., at International Society of Electrophysiology and Kinesiology [ISEK] congress). We will also work with the Journal of Electromyography and Kinesiology to periodically update the checklist when new evidence emerges to maintain the rigor and quality of EMG studies.

In summary, the CEDE-Check tool offers a comprehensive guideline for reporting EMG methodologies, especially for human studies. Although the current CEDE-Check focuses on human studies, its principles and recommendations could potentially be adapted for studies on experimental animals. The adaptation of the CEDE-Check for animal studies presents some challenges (Valentin & Zsoldos, 2016), such as differences in muscle physiology, electrode placement, and ethical considerations. Future research could explore ways to address these challenges and further develop the CEDE-Check to accommodate animal research in the field of EMG. By promoting standardization, transparency, and rigor in EMG research, the CEDE-Check tool aims to augment research quality and impact.

5. Conclusion

We used a Delphi consensus technique to develop a checklist for reporting and appraising the methods used in EMG studies. It is expected that the use of the CEDE-Check tool will enhance the quality of data collection and reporting in EMG studies. The checklist promotes consistency, transparency, and reproducibility of outcomes. Researchers are encouraged to adopt and adhere to the checklist in their EMG studies, which is a practice that must be endorsed by journal editors.

Funding

MML is supported by the European Research Council Grant (ERC-2014- CoG-646923_DBSModel). PWH is supported by an NHMRC Investigator grant (APP1102905). MCK was supported by the NHMRC Program Grant (APP1132524), Partnership Project (APP1153439) and Practitioner Fellowship (APP1156093). AH is supported by Slovenian Research Agency (projects J2-1731 and L7-9421 and Program funding P2-0041). FH is supported by the French government, through the UCAJEDI Investments in the Future project managed by the National Research Agency (ANR) with the reference number ANR-15-IDEX-01. DF is supported by the European Research Council (ERC; 810346) and by the Royal Society (Wolfson Research Merit Award).

CRediT authorship contribution statement

Manuela Besomi: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration. **Valter Devecchi:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Deborah Falla:** Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing, Supervision. **Kevin McGill:** Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing, Supervision. **Matthew C. Kiernan:** Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing, Supervision. **Roberto Merletti:** Conceptualization, Writing - Original Draft, Writing - Review & Editing, Supervision. **Jaap H. van Dieën:** , Writing - Review & Editing. **Kylie Tucker:** , Writing - Review & Editing. **Edward A. Clancy:** , Writing - Review & Editing. **Karen Søgaard:** Writing - Review & Editing. **François Hug:** Writing - Review & Editing. **Richard G. Carson:** Writing - Review & Editing. **Eric Perreault:** Writing - Review & Editing. **Simon Gandevia:** Writing - Review & Editing. **Thor Besier:** Writing - Review & Editing. **John C. Rothwell:** Writing - Review & Editing. **Roger M. Enoka:** Writing - Review & Editing. **Aleš Holobar:** Writing - Review & Editing. **Catherine Disselhorst-Klug:** Writing - Review & Editing. **Tim Wrigley:** Writing - Review & Editing. **Madeleine Lowery:** Writing - Review & Editing. **Dario Farina:** Writing - Review & Editing. **Paul W. Hodges:** Conceptualization, Methodology, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The CEDE group wishes to acknowledge the contribution of Prof. Dario G. Liebermann, the special editor for this series, for his critical assessment of the first version of this paper which substantially helped in refining it. We acknowledge the financial and intellectual support provided by the International Society of Electrophysiology and Kinesiology (ISEK) for the CEDE project.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jelekin.2024.102874.

References

Basmajian, J.V., De Luca, C.J., 1985. Muscles Alive: their functions revealed by electromyography. Williams & Wilkins.

Besomi, M., Hodges, P.W., Van Dieën, J., Carson, R.G., Clancy, E.A., Disselhorst-Klug, C., Holobar, A., Hug, F., Kiernan, M.C., Lowery, M., McGill, K., Merletti, R., Perreault, E., Søgaard, K., Tucker, K., Besier, T., Enoka, R., Falla, D., Farina, D., et al., 2019. Consensus for experimental design in electromyography (CEDE) project: Electrode selection matrix. J Electromyogr Kinesiol 48, 128–144. https://doi.org/10.1016/j.jelekin.2019.07.008.

Besomi, M., Hodges, P.W., Clancy, E.A., Van Dieën, J., Hug, F., Lowery, M., Merletti, R., Søgaard, K., Wrigley, T., Besier, T., Carson, R.G., Disselhorst-Klug, C., Enoka, R.M., Falla, D., Farina, D., Gandevia, S., Holobar, A., Kiernan, M.C., McGill, K., et al., 2020. Consensus for experimental design in electromyography (CEDE) project: Amplitude normalization matrix. J Electromyogr Kinesiol 53, 102438. https://doi.org/10.1016/j.jelekin.2020.102438.

Campanini, I., Merlo, A., Degola, P., Merletti, R., Vezzosi, G., Farina, D., 2007. Effect of electrode location on EMG signal envelope in leg muscles during gait. J Electromyogr Kinesiol 17 (4), 515–526. https://doi.org/10.1016/j.jelekin.2006.06.001.

Castroflorio, T., Farina, D., Bottin, A., Piancino, M.G., Bracco, P., Merletti, R., 2005. Surface EMG of jaw elevator muscles: effect of electrode location and inter-electrode distance. J Oral Rehabil 32 (6), 411–417. https://doi.org/10.1111/j.1365-2842.2005.01442.x.

Cisnal, A., Pérez-Turiel, J., Fraile, J.C., Sierra, D., Fuente, E.d.l., 2021. RobHand: A hand exoskeleton with real-time EMG-driven embedded control. Quantifying hand gesture recognition delays for bilateral rehabilitation. IEEE Access 9, 137809–137823. https://doi.org/10.1109/ACCESS.2021.3118281.

Clancy, E.A., Morin, E.L., Merletti, R., 2002. Sampling, noise-reduction and amplitude estimation issues in surface electromyography. Journal of Electromyography and Kinesiology 12 (1), 1–16. 10.1016/S1050-6411(01)00033-5.

Clancy, E.A., Morin, E.L., Hajian, G., Merletti, R., 2023. Tutorial. Surface electromyogram (sEMG) amplitude estimation: Best practices. Journal of Electromyography and Kinesiology 72, 102807. 10.1016/j.jelekin.2023.102807.

Del Vecchio, A., Holobar, A., Falla, D., Felici, F., Enoka, R., & Farina, D. 2020. Tutorial: analysis of motor unit discharge characteristics from high-density surface EMG signals. Journal of Electromyography and Kinesiology, 53, 102426. https://www.sciencedirect.com/science/article/pii/S1050641120300419?via%3Dihub.

Eby, L.T., Shockley, K.M., Bauer, T.N., Edwards, B., Homan, A.C., Johnson, R., Lang, J.W.B., Morris, S.B., Oswald, F.L., 2020. Methodological checklists for improving research quality and reporting consistency. Industrial and Organizational Psychology 13 (1), 76–83. https://doi.org/10.1017/iop.2020.14.

Farina, D., Merletti, R., Nazzaro, M., Caruso, I., 2001. Effect of joint angle on EMG variables in leg and thigh muscles. IEEE Engineering in Medicine and Biology Magazine 20 (6), 62–71. https://doi.org/10.1109/51.982277.

Farina, D., Cescon, C., Merletti, R., 2002. Influence of anatomical, physical, and detection-system parameters on surface EMG. Biol Cybern 86 (6), 445–456. https://doi.org/10.1007/s00422-002-0309-2.

Farina, D., Merletti, R., Enoka, R., 2014. The extraction of neural strategies from the surface EMG: an update. Journal of Applied Physiology 117 (11), 1215–1230. https://doi.org/10.1152/japplphysiol.00162.2014.

Gallina, A., Disselhorst-Klug, C., Dario Farina, R.M., Besomi, M., Holobar, A., Enoka, R.M., Hug, F., Falla, D., Søgaard, K., McGill, K., Clancy, E.A., Carson, R.G., van Dieën, J.H., Gandevia, S., Lowery, M., Besier, T., Kiernan, M.C., Rothwell, J.C., Tucker, K., Hodges, P.W., 2022a. Consensus for experimental design in electromyography (CEDE) project: High-density surface electromyography matrix. Journal of Electromyography and Kinesiology 64, 102656.

Gallina, A., Disselhorst-Klug, C., Farina, D., Merletti, R., Besomi, M., Holobar, A., Enoka, R.M., Hug, F., Falla, D., Sogaard, K., McGill, K., Clancy, E.A., Carson, R.G., van Dieen, J.H., Gandevia, S., Lowery, M., Besier, T., Kiernan, M.C., Rothwell, J.C., et al., 2022b. Consensus for experimental design in electromyography (CEDE) project: High-density surface electromyography matrix. J Electromyogr Kinesiol 64, 102656. https://doi.org/10.1016/j.jelekin.2022.102656.

Herak, M., & Zubčević, T. 2022. Methods for Analysis of EMG Signals: Systematic Review. 2022 11th Mediterranean Conference on Embedded Computing (MECO).

Hermens, H.J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., Disselhorst-Klug, C., Hägg, G., 1999. European recommendations for surface electromyography. Roessingh Research and Development 8 (2), 13–54.

Hodges, P.W., 2020. Editorial: Consensus for experimental design in electromyography (CEDE) project. J Electromyogr Kinesiol 50, 102343. https://doi.org/10.1016/j.jelekin.2019.07.013.

Hu, X.L., Tong, K.-Y., Song, R., Zheng, X.J., Leung, W.W.F., 2009. A comparison between electromyography-driven robot and passive motion device on wrist rehabilitation for chronic stroke. Neurorehabilitation and Neural Repair 23 (8), 837–846. https://doi.org/10.1177/1545968309338191.

Jünger, S., Payne, S.A., Brine, J., Radbruch, L., Brearley, S.G., 2017. Guidance on conducting and REporting DElphi studies (CREDES) in palliative care: Recommendations based on a methodological systematic review. Palliat Med 31 (8), 684–706. https://doi.org/10.1177/0269216317690685.

Keshwani, N., McLean, L., 2015. State of the art review: Intravaginal probes for recording electromyography from the pelvic floor muscles. Neurourol Urodyn 34 (2), 104–112. https://doi.org/10.1002/nau.22529.

Madeleine, P., Bajaj, P., Søgaard, K., Arendt-Nielsen, L., 2001. Mechanomyography and electromyography force relationships during concentric, isometric and eccentric contractions. J Electromyogr Kinesiol 11 (2), 113–121. https://doi.org/10.1016/s1050-6411(00)00044-4.

Martinek, R., Ladrova, M., Sidikova, M., Jaros, R., Behbehani, K., Kahankova, R., & Kawala-Sterniuk, A. 2021. Advanced bioelectrical signal processing methods: Past, present, and future approach—Part III: Other biosignals. Sensors, 21(18), 6064. https://www.mdpi.com/1424-8220/21/18/6064.

Martinez-Valdes, E., Enoka, R.M., Holobar, A., McGill, K., Farina, D., Besomi, M., Hug, F., Falla, D., Carson, R.G., Clancy, E.A., Disselhorst-Klug, C., van Dieën, J.H., Tucker, K., Gandevia, S., Lowery, M., Søgaard, K., Besier, T., Merletti, R., Kiernan, M.C., et al., 2023. Consensus for experimental design in electromyography (CEDE) project: Single motor unit matrix. Journal of Electromyography and Kinesiology 68, 102726. 10.1016/j.jelekin.2022.102726.

McManus, L., Lowery, M., Merletti, R., Søgaard, K., Besomi, M., Clancy, E.A., van Dieën, J.H., Hug, F., Wrigley, T., Besier, T., Carson, R.G., Disselhorst-Klug, C., Enoka, R.M., Falla, D., Farina, D., Gandevia, S., Holobar, A., Kiernan, M.C., McGill, K., et al., 2021a. Consensus for experimental design in electromyography (CEDE) project: Terminology matrix. Journal of Electromyography and Kinesiology 59, 102565.

McManus, L., Lowery, M., Merletti, R., Sogaard, K., Besomi, M., Clancy, E.A., van Dieen, J.H., Hug, F., Wrigley, T., Besier, T., Carson, R.G., Disselhorst-Klug, C., Enoka, R.M., Falla, D., Farina, D., Gandevia, S., Holobar, A., Kiernan, M.C., McGill, K., et al., 2021b. Consensus for experimental design in electromyography (CEDE) project: Terminology matrix. J Electromyogr Kinesiol 59, 102565. https://doi.org/10.1016/j.jelekin.2021.102565.

Merletti, R., Cerone, G., 2020. Tutorial. Surface EMG detection, conditioning and pre-processing: best practices. Journal of Electromyography and Kinesiology 54, 102440.

Merletti, R., Muceli, S., 2019. Tutorial. Surface EMG detection in space and time: Best practices. Journal of Electromyography and Kinesiology 49, 102363. 10.1016/j.jelekin.2019.102363.

Merletti, R. 1999. Standards for Reporting EMG Data. Journal of Electromyography and Kinesiology, 9(1), III-IV. https://isek.org/wp-content/uploads/2015/05/Standards-for-Reporting-EMG-Data.pdf.

Merletti, R. 2016. Applications in Proctology and Obstetrics. In Surface Electromyography : Physiology, Engineering, and Applications (pp. 392-407). https://doi.org/10.1002/9781119082934.ch14.

Murciego, L. P., Komolafe, A., Peřinka, N., Nunes-Matos, H., Junker, K., Díez, A. G., Lanceros-Méndez, S., Torah, R., Spaich, E. G., & Dosen, S. 2023. A Novel Screen-Printed Textile Interface for High-Density Electromyography Recording. Sensors, 23 (3), 1113. https://www.mdpi.com/1424-8220/23/3/1113.

Myers, A., Lin, D., He, H., Yong, Z., 2014. Novel wearable EMG sensors based on nanowire technology. Annu Int Conf IEEE Eng Med Biol Soc 2014, 1674–1677. https://doi.org/10.1109/embc.2014.6943928.

Schulz, K.F., Altman, D.G., Moher, D., 2010. CONSORT 2010 Statement: updated guidelines for reporting parallel group randomised trials. Trials 11, 32. https://doi.org/10.1186/1745-6215-11-32.

Stafford, R.E., Sapsford, R., Ashton-Miller, J., Hodges, P.W., 2010. A novel transurethral surface electrode to record male striated urethral sphincter electromyographic activity. J Urol 183 (1), 378–385. https://doi.org/10.1016/j.juro.2009.08.105.

Staudenmann, D., Roeleveld, K., Stegeman, D.F., van Dieen, J.H., 2010. Methodological aspects of SEMG recordings for force estimation–a tutorial and review. J Electromyogr Kinesiol 20 (3), 375–387. https://doi.org/10.1016/j.jelekin.2009.08.005.

Valentin, S., Zsoldos, R.R., 2016. Surface electromyography in animal biomechanics: A systematic review. J Electromyogr Kinesiol 28, 167–183. https://doi.org/10.1016/j.jelekin.2015.12.005.

Varadarajan, V., Blumin, J.H., Bock, J.M., 2013. State of the art of laryngeal electromyography. Current Otorhinolaryngology Reports 1 (3), 171–177. https://doi.org/10.1007/s40136-013-0017-6.

von der Gracht, H.A., 2012. Consensus measurement in Delphi studies: Review and implications for future quality assurance. Technological Forecasting and Social Change 79 (8), 1525–1536. 10.1016/j.techfore.2012.04.013.

von Elm, E., Altman, D.G., Egger, M., Pocock, S.J., Gøtzsche, P.C., Vandenbroucke, J.P., 2007. The strengthening the reporting of observational studies in epidemiology (STROBE) statement: guidelines for reporting observational studies. Ann Intern Med 147 (8), 573–577. https://doi.org/10.7326/0003-4819-147-8-200710160-00010.

Waggoner, J., Carline, J.D., Durning, S.J., 2016. Is there a consensus on consensus methodology? descriptions and recommendations for future consensus research. Acad Med 91 (5), 663–668. https://doi.org/10.1097/acm.0000000000001092.