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Gait & Posture 117 (2025) 72–77

Contents lists available at ScienceDirect

Gait & Posture

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

Status of surface electromyography assessment as part of clinical gait analysis in the management of patients with cerebral palsy – Outcomes of a Delphi process

Robert Reisig [a], Nathalie Alexander [b], Stéphane Armand [c], Gabor J. Barton [d], Harald Böhm [e], Christophe Boulay [f,g], Reinald Brunner [h], Anna Castagna [i], Mehrdad Davoudi [a], Eric Desailly [j], Kaat Desloovere [k,l], Chakravarthy U. Dussa [m,n], David Gasq [o,p], Raphaël Gross [q], Andreas Kranzl [r], Fabien Leboeuf [q], Tiziana Lencioni [i], Sylvia Ounpuu [s], Elyse Passmore [t,u,v], Dimitrios A. Patikas [w], Kristan A. Pierz [s], Erich Rutz [t,u], Firooz Salami [a], Céline Schreiber [x], Felix Stief [y], Pam Thomason [t], Marjolein M. van der Krogt [z], Sebastian I. Wolf [a,*]

[a] Clinic for Orthopedics, Heidelberg University Hospital, Germany
[b] Laboratory for Motion Analysis, Division of Paediatric Orthopaedics, Children's Hospital of Eastern Switzerland, Switzerland
[c] Kinesiology Laboratory, Geneva University Hospitals, University of Geneva, Switzerland
[d] Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, UK
[e] Orthopädische Kinderklinik, BZ Aschau, Germany
[f] Gait lab, pediatric orthopaedic surgery department, Children's Timone Hospital, France
[g] Institut des Sciences du Mouvement (ISM), Equipe DynamiCC, Aix-Marseille Université, France
[h] University Children's Hospital Basel, Switzerland
[i] IRCCS Fondazione Don Carlo Gnocchi, Milan, Italy
[j] Fondation Ellen Poidatz, Pôle Recherche & Innovation, Saint-Fargeau-Ponthierry, France
[k] KU Leuven Department of Rehabilitation Sciences, Leuven, Belgium
[l] Clinical Motion Analysis Laboratory, University Hospital Leuven, Leuven, Belgium
[m] Department of Trauma and Orthopaedic Surgery, University Hospital Erlangen, Germany
[n] Paediatric Orthopaedics, Department of Orthopaedics and Traumatology, Klinikum Großhadern, Ludwig-Maximillian-Universität, Munich, Germany
[o] Toulouse NeuroImaging Center, Université de Toulouse, Inserm, Paul Sabatier University, Toulouse, France
[p] Department of Clinical Physiology, Motion Analysis Center, Toulouse University Hospital, Toulouse, France
[q] Nantes University Hospital Motion Lab, Nantes Université, CHU Nantes, Movement - Interactions - Performance, Nantes, France
[r] Laboratory for Gait and Movement Analysis, Orthopaedic Hospital Speising, Vienna, Austria
[s] Center for Motion Analysis, Connecticut Children's Medical Center, Farmington, CT, USA
[t] Hugh Williamson Gait Analysis Laboratory, Royal Children's Hospital, Melbourne, Australia
[u] Department of Medicine, Dentistry and Health Sciences, University of Melbourne, Australia
[v] Developmental Imaging, Murdoch Children's Reasearch Institute, Melbourne, Australia
[w] Laboratory of Neuromechanics, School of Physical Education & Sports Science at Serres, Aristotle University of Thessaloniki, Greece
[x] Centre National de Rééducation Fonctionnelle et de Réadaptation - Rehazenter, LAMP - Laboratoire d'Analyse du Mouvement et de la Posture, Luxembourg, Luxembourg
[y] Berufsgenossenschaftliche Unfallklinik Frankfurt/Main, BG Service and Rehabilitation Center, Function and Motion Lab, Frankfurt/Main, Germany
[z] Amsterdam University Medical Center | VUmc · Rehabilitation Medicine Clinic, Amsterdam, the Netherlands

ARTICLE INFO

Keywords:
Cerebral Palsy
Dynamic EMG
Consensus
Delphi
Muscle activity

ABSTRACT

Background: The assessment of gait disorders in patients with neuromotor conditions, such as cerebral palsy (CP), has been a focus of clinical and research attention, with electromyography (EMG) offering a nuanced understanding of neurological and neuromuscular disorders. However, the interpretation of EMG data in the context of gait analysis remains challenging due to the complexity of neuromotor dynamics and variability in assessment methodologies.

Research question: To which consensus can we get in a group of experts in the fields of neurological and neuromuscular disorders, biomechanics, and clinical gait analysis to establish standardized protocols and a

* Correspondence to: Clinic for Orthopedics, Schlierbacher Landstr. 200a, Heidelberg 69118, Germany.
E-mail address: Sebastian.Wolf@med.uni-heidelberg.de (S.I. Wolf).

https://doi.org/10.1016/j.gaitpost.2024.12.009
Received 26 June 2024; Received in revised form 8 November 2024; Accepted 8 December 2024
Available online 9 December 2024

common language for the measurement and analysis of EMG data in gait disorders, particularly in people living with CP?

Methods: A three-round Delphi process was conducted from February to September 2023 to gather opinions of 53 experts on the use of surface EMG data during gait in the context of CP. The surveys were conducted using the tool 'SoSci Survey' with a focus on free-text answers.

Results: The experts agreed on the usefulness of EMG data, but a consensus on specific clinical decisions involving EMG could not be reached. Additionally, the study provides a terminological framework for EMG evaluation during gait and a comprehensive list of practical problems and solutions, when evaluating EMG data. The study indicates that, despite a general community consensus on the ideal approaches to data processing and evaluation, these methods are not commonly implemented in a standardized manner. Both raw and enveloped data are widely used in clinical routines, however, the protocol for generating normative data lacks consistency across gait laboratories.

Significance: The study suggests that while there may be differences in the way EMG data is analyzed, there is a shared understanding of the key features that are relevant for gait analysis.

1. Introduction

In medical science, the assessment of gait disorders, particularly in patients with neurological and neuromuscular disorders, such as cerebral palsy (CP), has been an area of significant clinical and research focus. The study of gait patterns through surface electromyography (EMG) offers a nuanced understanding of neurological and muscular function. Recommendable technical standards have been set by the SENIAM project especially regarding equipment, skin preparation, electrode placement and fixation, as well as quality assurance testing [1]. However, despite advances in the standardized methods of the processing of EMG signal, the interpretation of EMG data in the context of gait analysis remains challenging due to the intricate nature of neurological and neuromuscular dynamics and the variability in assessment methodologies [2,3].

The primary issue stems from the absence of standardized protocols and a shared terminology for measuring and analyzing EMG data, which impedes the synthesis of findings and, by extension, the formulation of robust treatment plans [4,5]. Consequently, there is a critical gap in our ability to classify gait patterns based on EMG findings in the context of gait analysis in a manner that is both clinically relevant and universally applicable.

The Delphi method [6] presents a promising approach to tackling these challenges. The answers given in each survey round were summarized and reflected back to the panel in subsequent rounds. By engaging a panel of experts, this study aimed to establish standardized protocols and a common language for the measurement and analysis of EMG data in gait disorders, particularly in patients with CP.

2. Methods

From February until September 2023 a three-round Delphi process was conducted to gather expert opinions on the use of EMG data during gait in the context of CP. The panel, comprising of 108 international experts in the field, including researchers, clinicians, and engineers, were invited via email to participate in this Delphi process. With only very few exceptions they were directly known by last author via their affiliation with the European Society for Movement Analysis in Adults and Children (ESMAC) and their participation at annual meetings over at least five years. The first round started on the same day as the invitation email was sent, and each round remained accessible for at least one month. Reminders were sent to participants, and the actual time frame of each round was extended by some days to include answers from late responders. About half of the experts (53 i.e. 49 %) responded to this first invitation and this response (round 1) was kept anonymous. Fifteen participants dropped out after the first round (14 %) and hence 38 participants responded in round 2 and gave consent to be known by name. An equal number (11) of participants (29 %) was engineer, movement scientist, and physician (surgeon or physical medicine and rehabilitation physician), respectively, and five experts (13 %) were physiotherapists. Thirty-two experts (84 %) were using EMG predominantly in clinical context, with six experts using it primarily for research purposes. The experts worked at the time of the survey in 13 different countries: Australia (3), Austria (1), Belgium (3), France (6), Germany (5), Greece (1), Italy (2), Luxembourg (1), Netherlands (1), Poland (1), Switzerland (6), United Kingdom (4), and United States of America (4). Of these 38 experts four did not follow-up round 3 due to unknown reasons.

For conducting the surveys, the tool 'SoSci Survey' (a web-based survey system) [7] was used. Participants could fill out the HTML forms on their own devices at a time of their choice. The Delphi organizers (authors R.R. and S.I.W.) formulated the questions, which were presented in various formats, emphasizing free-text responses. Participants had the option to skip questions.

Email was the primary method of communication between the participants and the Delphi organizers. The preliminary results were presented at the ESMAC 2023 conference in Athens [8] and some further discussion was held on this occasion.

The participants remained anonymized to each other so that biases could be reduced. For practical reasons the Delphi organizers were not blinded.

The three rounds built on top of each other. The first round (53 participants) was designed to establish a ground for the next rounds, with a general overview on EMG that could be completed easily. It focused on the general practice of each center, including which muscles would typically be assessed, how the data would be described for assessment in clinical decision making, i.e. to name descriptive terms, and further to rate reliability and usefulness for the decision process. The descriptive terms which were named by the panel were then checked for similarities and redundancies by the Delphi organizers and were further grouped into features describing either time or intensity aspects of EMG signals or by features describing the signal relation between muscles. The second round (38 participants) reflected the signal feature description of round one, questioned in how far raw EMG signals or rather activity patterns (i.e. time-normalized and filtered EMG envelopes) are used for interpretation. Further, the use and needs for normative data were questioned in this round. The panel responses from the second round were streamlined by the Delphi organizers to condense precise statements on EMG interpretation for which approval rates were measured in the third round (34 participants).

Further, the panel was asked in round one to name treatment decisions based on EMG data which may be typical in their center. These responses were grouped by the Delphi organizers to specific muscles for refining the description of these treatment decisions in round two. Those treatments which were named most frequent where then followed-up in round three for rating agreement.

The study focused on EMG data during gait and primarily pertained to surface EMG, without making precise distinctions between surface EMG and more invasive methods.

3. Results

3.1. Value of EMG data in general

In the first round, participants were asked to rate the helpfulness and reliability of EMG information on a scale from 1 (not at all) to 5 (very). The results showed that most participants considered EMG data to be 'very helpful' (42 %) or 'somewhat helpful' (48 %), with only a few participants rating it as 'neutral' (6 %) or 'not really helpful' (6 %), and no one rating it as 'not at all helpful'.

Also, in the first round, perceived reliability was rated similarly, with most participants considering EMG data in their laboratory to be 'very reliable' (23 %) or 'somewhat reliable' (56 %), and only a few participants rating it 'neutral' (17 %) or 'not really reliable' (4 %), and no one rating it as 'not reliable at all'.

Participants were asked to explain their answer about perceived reliability in the first round. The answers provided a comprehensive overview of common problems and suggestions for quality assurance. Using these responses, the Delphi organizers introduced a framework that differentiated between inherent challenges in EMG measurements and those that could be addressed. This framework was widely accepted, with 94 % of participants endorsing it by the third round of discussions.

The following problems were named which are inherent to surface EMG measurements: Largely varying muscle size and muscle shape also in the context of deformities, variable amounts of skin and fat tissue, inability to detect deeper muscles, excessive sweat with loosening electrodes, as well as the absence of an intuitive correlation between muscle strength and signal activity which burdens interpretation. Interexaminer variability, variability in electrode placement, differences in skin preparation, artifacts, and lack of routine were named as measurement (quality) problems which may largely be minimized by quality assurance using standardized procedures with high quality equipment and frequent examiner training. Practical advice was offered for quality checks of EMG signals by visual inspection before and during examination to allow for electrode placement corrections, potentially supported by ultrasound control, as well as short electrode spacing for minimizing cross-talk.

In the final round, participants were asked to rate again the usefulness and importance of dynamic EMG data, reporting for the evaluation of patients with CP on a scale from 0 (not useful) to 100 (very useful). The results were similar to the results of the first round. The majority of participants still considered EMG data to be useful, with an average rating of 79 (median of 82) and an interquartile range of 23. The lowest response was 11, and the highest was 100.

3.2. Consensus on EMG descriptors

In the first round, participants were asked to identify explicit features of EMG (raw data or envelopes) that are relevant to the medical treatment of CP. The emerging terminology encompassed a wide range of descriptors, including descriptive terms such as 'absent activity' or 'prolonged activity', interpretive terms like 'spastic activity' or 'pathological activity', and other vocabulary that was difficult to categorize, such as 'sharp peaks' and 'inversion of phase'.

On this basis, the Delphi organizers proposed a classification system for subsequent rounds based on the most frequently used terms from the provided vocabulary, aiming to standardize the terminology for describing EMG during gait. The goal was to create a distinct and concise classification that covered the entire spectrum of relevant EMG features. The proposed classification was presented to the participants in round 2 %, and 92 % agreed that it was sufficient to describe EMG data. Some suggestions were made to modify the classification, which was subsequently refined and presented again in round 3.

The final classification uses terms within 3 categories:

1. Aspects in EMG regarding the time dimension can be described with these words: delayed, premature, prolonged, short, continuous, phasic, out of phase, onset, and cessation
2. Aspects in EMG regarding the intensity dimension can be described with these words: increased, reduced, and absent
3. Aspects in EMG regarding the relationship between muscles can be described with these words: co-contraction, asymmetry, and synergies

3.3. Value of specific EMG data

In the first round, participants were asked to list the muscles that are routinely measured in their laboratories. The results showed that tibialis anterior, rectus femoris, gastrocnemius and semimembranosus are the most measured muscles, with at least 85 % of participants selecting each of them. Vastus lateralis, soleus, peroneus longus, gluteus medius and biceps femoris were each selected by at least 40 % of participants (comp. Fig. 1).

3.4. Consensus on EMG reporting

In the first round, participants were asked whether they use normative data in their laboratories and, if so, how they obtain it. A total of 76 % percent responded "yes," 14 % answered "sometimes," and 10 % do not use normative data. Participants were also asked to explain how they obtained their normative data (free text input). Many laboratories use self-obtained reference data (51 %), while others rely on the literature or hardware manufacturer (34 %).

In the second round, participants were asked about the sample size of their normative data and their opinions on the minimum required number of subjects to create normative data. The answers for the actual sample sizes ranged from 10 to 106, with an average of 42, a median of 33.5, and an interquartile range of 30. For the minimal required number, the answers ranged from 10 to 100, with an average of 33, a median of 20, and an interquartile range of 10. Additionally, participants were asked about their opinions on age-matching normative data to the participant's age. Twenty-four percent believed it was necessary, 49 % thought it was advisable, 24 % saw no substantial benefit, 3 % believed it was not advisable, and no one chose the option that it was harmful.

Based on the information and comments from round 2, the Delphi organizers proposed two statements for participants to agree or disagree with in round 3:

1. *Based on the summary outlined above [results from round 1], can you agree with the majority of experts that: a) It is helpful and reasonable to include EMG reporting with reference data from two age groups, one younger than 8 years and one older than 8 years? b) Speed-matched reference data might be helpful but is typically not feasible in clinical routine reporting?*
2. *Based on the summarized data above [results from round 1], can you agree with the majority of experts that it is sufficient to have EMG reference data available based on a sample size (per age group) of 20?*

Seventy-one percent of the participants agreed with the first statement, 24 % disagreed, and 6 % opted out. Eighty-eight percent agreed with the second statement, 9 % disagreed, and 3 % opted out. The reasons for disagreeing varied. Several participants did not agree with age groups in general, others did not agree with the split at the age of 8, some did not believe speed-matched data were beneficial at all, and the sample size of 20 was perceived as too high or too low by different participants.

In the first round, participants were asked whether they utilize raw data, envelopes, or other methods for their EMG assessments. It was possible to select multiple options. Seventy-two percent selected 'raw data', 55 % selected 'envelopes', and 15 % selected 'other'. Participants who selected 'envelopes' or 'other' were asked to elaborate on the

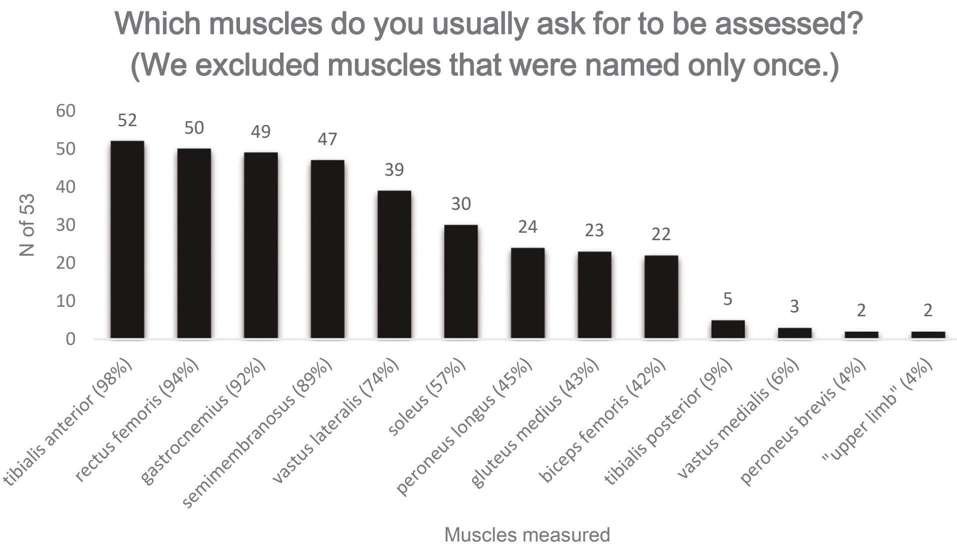

Fig. 1. Feedback round 1 to the question "Which muscles do you usually ask for to be assessed?" (excluded are muscles that were named only once and upper limb muscles are summarized).

enveloping process and comment on what they meant by 'other'. The responses revealed that the question had been interpreted differently by various participants. For instance, some understood 'raw data' as the absolute raw signal, while others applied filters, such as a high pass filter, and labeled the result 'raw data'. Additionally, some EMG system manufacturers automatically apply built-in data processing that end-users may not be aware of. The data processing methods appeared to vary among the panel.

In the second round, participants were asked to elaborate on their use of raw data and enveloped data separately. The Delphi organizers defined 'enveloping' as a computational process typically consisting of rectifying, filtering, smoothing, possibly averaging across trials, and possibly normalizing the amplitude. The answers showed a diverse use of EMG data processing and its subsequent evaluation. For example, several laboratories use enveloped data primarily for research, and multiple participants stated that they do not use enveloped data at all.

Given this information, the Delphi organizers proposed a statement for the third round to find consensus:

Question (Round 3): "Based on the summary outlined above [results from rounds 1 & 2] can you agree with the majority of experts that it is: a) important to report EMG raw data for quality assurance? b) reporting of EMG envelopes is helpful and reasonable for clinical interpretation (and for research questions)?"

Ninety-four percent of the participants agreed with the statement, and 6 % disagreed for various reasons.

3.5. Consensus on EMG based decisions

In addition to the issues about reliability and value of EMG data, its potential use in clinical decision making was part of the Delphi process as well. In the first round, participants were asked to describe such a process, but the responses were highly diverse, covering surgical procedures, botulinum toxin injections, physiotherapeutic decisions, and various muscles. No clear patterns emerged within the panel.

In the second round, the question about decision processes was focused more on specific muscles. Participants were asked to describe any medically relevant EMG pattern associated with each muscle which were named most frequently in round one (i.e. more than 40 %, in Fig. 1). While the responses were more comprehensive than in the first round, common features were limited.

The Delphi organizers used the provided information from the previous rounds to draft three possible rules with the intention of achieving consensus among the participants. The rules were formulated based on patterns in the responses. However, due to the diverse opinions, the rules were quite unspecific:

1. *"Increased swing phase activity of the rectus femoris in patients with CP with a stiff knee is typically an indication for rectus transfer surgery. Furthermore, it is necessary to factor in the EMG of the vastus (medialis or lateralis) to exclude crosstalk. The actual treatment decision may depend on other factors as well, such as kinetic and kinematic data."; (65 % confirmation in round 3)*
2. *"Absent swing phase activity of tibialis anterior plays a significant role in treatment of drop foot for patients with CP. The actual treatment decision may depend on other factors as well, such as kinetic and kinematic data."; (77 % confirmation in round 3)*
3. *"Premature activity of calf muscles in equinus gait may prevent surgical decisions such as Achilles tendon lengthening in patients with CP. The actual treatment decision may depend on other factors as well, such as kinetic and kinematic data"; (56 % confirmation in round 3)*

The final approval rating in round 3 ranged between 50 % and 80 % for all three rules, indicating a lack of consensus. Afterwards, still in round 3, participants were asked to elaborate on their decision to approve or disapprove. The answers revealed no clear patterns for the reasons to disapprove. Some participants disagreed due to the rule's specificity or details, while others disagreed with the rule as a whole. Many answers indicated that participants were hesitant to settle on a specific decision process and instead considered EMG as one of several variables, including kinetic and kinematic data, which are believed to be more relevant.

Additionally, the responses of the first and second rounds suggested an association between:

1. hamstring muscle EMG and lengthening surgeries, and
2. gluteus medius muscle EMG and derotation osteotomy.

However, the answers of the third round failed to confirm any consensus regarding these aspects.

Furthermore, in many responses of the second and third rounds, the wording used for describing these decision processes did not incorporate the provided classification (Consensus on EMG descriptors) which was already agreed on earlier in round 2. Instead, it appeared that many participants relied on their accustomed terminology, which varies widely.

4. Discussion

The results of our Delphi study highlight the variability in EMG evaluation practices during gait across different laboratories, indicating a lack of standardization in the field. Despite the absence of consensus on specific methods, the study was able to establish a classification of features that could serve as a foundation for a common terminology. This finding is particularly relevant, as it suggests that while there may be differences in the way EMG data is analyzed, there is a shared understanding of the key features that are relevant for gait analysis.

The study also revealed that the use of EMG data in clinical practice is not straightforward. Participants reported that they rely heavily on raw data, which can be challenging to interpret, and there was a lack of consensus on how to process and analyze the data. Even though this issue was not addressed directly in the Delphi process, it turned out that signal normalization is an issue under strong debate amongst experts. These transformations may come with both advantages and limitations [9] which should be considered carefully.

The perceived usefulness of EMG data during gait analysis is a significant finding of our study. Despite the variability in methods and lack of consensus on specific clinical processes, participants generally agreed that EMG data is valuable for gait analysis. A recent work on gait analysis standardization showed that in fact 81 % of clinical gait laboratories in Europe use EMG regularly [10]. This may suggest that there is a recognition of the potential benefits of EMG data.

One possible explanation for the lack of consensus on EMG evaluation methods is the complexity and subjective nature of the data. Additionally, the clinical application of EMG data requires a deep understanding of muscle physiology, neural control of movement, gait mechanics, and data processing techniques, which may contribute to the variability in evaluation methods.

There is a need for more research on the development and validation of standardized EMG evaluation methods that can be applied across different laboratories. The technical steps should be the same to achieve the same results, though the interpretation of these results for treatment may still diverge. Furthermore, there is a need for more education which can provide clinicians and researchers with the necessary skills and knowledge to effectively evaluate EMG data. Future research may focus on utilizing indices such as the co-contraction index [11] and index of asymmetry [12] or methods quantifying muscle synergy, which may enhance the interpretability and clinical application of the data. Gaining a deeper understanding of the underlying pathologies associated with cerebral palsy, such as spasticity, would provide stronger evidence for interpreting EMG results.

5. Limitations

Delphi consensus studies can typically only give limited evidence as they summarize experience and opinions of experts. Their choice may have been biased in favor of European participants as they were recruited exclusively amongst participants of ESMAC conferences which, nevertheless, are international. Potentially, the complexity of aggregating responses especially with regards to signal processing and amplitude normalization may have led to an oversimplified outcome. Specifically, the use of compound variables describing muscle synergies such as [13] which lately has raised scientific attention has not been followed up in this Delphi process. Further, the initial framing of questions may have not been ideal as it emerged that not all experts limited their answers to the application of surface EMG in gait of people living with CP and thereby indirectly burdened the process of reaching consensus.

6. Conclusion

In summary, our Delphi study offers an extensive examination of contemporary surface EMG evaluation practices in clinical gait analysis laboratories. The community exhibits varied perspectives regarding the integration of EMG into routine gait assessments. While the data holds significant promise, currently well-defined clinical protocols utilizing EMG information are lacking. Nevertheless, there was high consensus about how EMG signals are to be described. Future such initiatives should be started to harmonize EMG reporting in gait analysis labs to ultimately strengthen the potential of using this information for treatment decision making.

CRediT authorship contribution statement

David U Gasq: Writing – review & editing. **Raphaël Gross:** Writing – review & editing. **Kaat Desloovere:** Writing – review & editing. **Chakravarthy U Dussa:** Writing – review & editing. **Mehrdad Davoudi:** Writing – review & editing. **Eric Desailly:** Writing – review & editing. **Reinald Brunner:** Writing – review & editing. **Anna Castagna:** Writing – review & editing. **Marjolein M van der Krogt:** Writing – review & editing. **Sebastian Immanuel Wolf:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Christophe Boulay:** Writing – review & editing. **Pam Thomason:** Writing – review & editing. **Gabor J. Barton:** Writing – review & editing. **Harald Böhm:** Writing – review & editing. **Céline Schreiber:** Writing – review & editing. **Nathalie Alexander:** Writing – review & editing. **Felix Stief:** Writing – review & editing. **Stéphane Armand:** Writing – review & editing. **Erich Rutz:** Writing – review & editing. **Firooz Salami:** Writing – review & editing, Data curation. **Robert Reisig:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dimitrios A Patikas:** Writing – review & editing. **Kristan A Pierz:** Writing – review & editing. **Sylvia Ounpuu:** Writing – review & editing. **Elyse Passmore:** Writing – review & editing. **Fabien Leboeuf:** Writing – review & editing. **Tiziana Lencioni:** Writing – review & editing. **Andreas Kranzl:** Writing – review & editing.

Declaration of Competing Interest

“Each of the authors has read and concurs with the content in the final manuscript. The material within has not been and will not be submitted for publication elsewhere except as an abstract." There is no conflict of interests.

Acknowledgements

We thank the Deutsche Forschungsgemeinschaft, Germany, for funding this project: DFG grant WO 1624/8-1.

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