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Consensus for Experimental Design in Electromyography (CEDE) project: Amplitude normalization matrix

--Manuscript Draft--

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Abstract:	The general purpose of normalization of EMG amplitude is to enable comparisons between participants, muscles, measurement sessions or electrode positions. Normalization is necessary to reduce the impact of differences in physiological and anatomical characteristics of muscles and surrounding tissues. Normalization of the EMG amplitude provides information about the magnitude of muscle activation relative to a reference value. It is essential to select an appropriate method for normalization with specific reference to how the EMG signal will be interpreted, and to consider how the normalized EMG amplitude may change when interpreting it under specific conditions. This matrix, developed by the Consensus for Experimental Design in Electromyography (CEDE) project, presents six approaches to EMG normalization: 1) Maximal voluntary contraction (MVC) in same task/context as the task of interest, 2)

	Standardized isometric MVC (which is not necessarily matched to the contraction type in the task of interest), 3) Standardized submaximal task (isometric/dynamic) that can be task-specific, 4) Peak/mean EMG amplitude in task, 5) Non-normalized, and 6) Maximal M-wave. General considerations for normalization, features that should be reported, definitions, and "pros and cons" of each normalization approach are presented first. This information is followed by recommendations for specific experimental contexts, along with an explanation of the factors that determine the suitability of a method, and frequently asked questions. This matrix is intended to help researchers when selecting, reporting and interpreting EMG amplitude data.
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Response to Reviewers:	We have provided a detailed response (see attached files).

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Editor Dario G Liebermann
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June 3, 2020

Dear Editor,

RE: Consensus for Experimental Design in Electromyography (CEDE) project: Amplitude normalization matrix

The authors wish to thank the JEK editorial team and the reviewer for the opportunity to address their comments.

We have addressed the comments made by the reviewer and responded every change made point by point.

Please find attached our detailed responses to each of the reviewer's comments and our manuscript with revisions identified through track changes. To ensure we have addressed all comments, we have produced a table where we have given each comment an identifier (e.g., 'Comment') in the left column. In the right column, each comment has a response and, where required, a revision (e.g., labelled 'Revision'). Line numbers are added to the revised track changes document.

Please be advised that the author biography will be provided later.

Yours sincerely,

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Response to reviewer's comments

#	Comment	Response and revision
1	I read this second paper of the series and I found it focused and informative. Yet, there are a few minor points that could be clarified and still be improved in the last paper draft for JEK readers: 1-The paper does not question whether EMG amplitude-normalization without time-normalization is valid. Please refer to this issue, which in my opinion, is pertinent to any time-series analyses.	Although we understand the comment from the reviewer and agree that this is an important issue for analysis and interpretation of EMG, we aimed to focus this matrix on the principles and recommendations for EMG normalization of amplitude measures. Time-normalization is a separate issue that serves for a different purpose and is planned for detailed discussion in a separate matrix related to temporal issues of the EMG signal.
2	How does the normalized amplitude EMG (the e.g., relative to MVC) and the EMG normalized with respect to time (total duration of EMG activity) relate to muscle activation?	Please refer to response #1
3	Lines 100-102 presents redundant information because the same has been hinted before, in lines 94-95	Thank you for your suggestion, we agree that this is redundant and we have removed the example.
4	Lines 106-107 seems redundant because you are mentioning the same later in the manuscript	We believe this refers to the statement "Various normalization methods have been described [Burden, 2010; Merlo & Campanini, 2016], such as…". We consider that this statement is necessary to introduce the topic of this paragraph and prefer to retain it.
5	line 227 "......new empirical data emerges...": data emerge (delete "s")	We have removed the "s".
6	Lines 256-257. The normalization method may also depend on type of population (not only on muscle or task, or the research question asked). For example, what type of normalization would be suitable in the case of research in healthy normally-developed children?	We agree with the reviewer that this an important consideration and have referred to some examples of this in the text and paper, e.g. pain population. We agree that this needs to be further emphasised and broadened. We done this in several places as follows. <u>Revision</u> Introduction. Paragraph 4, Lines 131-132 (new text in bold). Edited/added text: "Further, in some task contexts **or in some participant groups (e.g., people with pain, children, etc.)**, the optimal method for EMG normalization may not necessarily be **possible or** practical." Discussion. Paragraph 2, Lines 230-245 (new text in bold).

		Edited/added text: “In some cases there is no method available to answer the research question (e.g., when participants cannot voluntarily activate a muscle [e.g., motor paralysis after cerebrovascular accident] or have difficulty activating the muscle [e.g., pelvic floor muscle activation in urinary incontinence, **or pediatric population**]). In those cases, where no ideal method is available, interpretation of the EMG amplitude may depend on the use of multiple sub-optimal methods, and consideration the convergence/divergence arising from these.”
7	Table 2: highlight in bold, those pieces of text where the reader is required to pay special attention; e.g., in assumptions such as: "....assuming a linear relation between activation and force (although the relation is not always linear.).." [in teh last 1/3 of the first page in table 2]. Also, in the second page of the same table [top paragraph], it reads "... although the relation between EMG amplitude and muscle activation might not be perfectly linear". The non-linear relation between muscle activation, EMG amplitude and force output should perhaps be highlighted.	<u>Response</u> We have highlighted in bold the sections suggested by the reviewer.
8	The paper deals with existing methods. Any suggestion about a novel or different way to normalize time-varying EMG signals?	<u>Response</u> Please refer to response #1 regarding time-normalization. New methods for EMG recording may become available, and recommendations provided will likely change over time as new empirical evidence emerges. This matrix will need to be updated accordingly. The paper does provide an indication that updates will be needed when “new methods become available”. We chose to leave this open but could add some examples if that is preferred. We have also added a sentence that describes “when no ideal method is available, interpretation of the EMG amplitude may depend on the use of multiple sub-optimal methods, and consideration the convergence/divergence arising from these”.

9	Last page in "frequently asked questions"; based on my previous concern I would ask also: Is time-normalization also required?	Response As previously commented, because a separate matrix dealing with temporal issues of the EMG signal will be prepared to address this (and other concerns), we believe that the FAQs section should not include this question.

Abstract

The general purpose of normalization of EMG amplitude is to enable comparisons between participants, muscles, measurement sessions or electrode positions. Normalization is necessary to reduce the impact of differences in physiological and anatomical characteristics of muscles and surrounding tissues. Normalization of the EMG amplitude provides information about the magnitude of muscle activation relative to a reference value. It is essential to select an appropriate method for normalization with specific reference to how the EMG signal will be interpreted, and to consider how the normalized EMG amplitude may change when interpreting it under specific conditions. This matrix, developed by the Consensus for Experimental Design in Electromyography (CEDE) project, presents six approaches to EMG normalization: 1) Maximal voluntary contraction (MVC) in same task/context as the task of interest, 2) Standardized isometric MVC (which is not necessarily matched to the contraction type in the task of interest), 3) Standardized submaximal task (isometric/dynamic) that can be task-specific, 4) Peak/mean EMG amplitude in task, 5) Non-normalized, and 6) Maximal M-wave. General considerations for normalization, features that should be reported, definitions, and "pros and cons" of each normalization approach are presented first. This information is followed by recommendations for specific experimental contexts, along with an explanation of the factors that determine the suitability of a method, and frequently asked questions. This matrix is intended to help researchers when selecting, reporting and interpreting EMG amplitude data.

Key words: Electromyography; Muscle activation; Amplitude normalization; Consensus

Consensus for Experimental Design in Electromyography (CEDE) project: Amplitude normalization matrix

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Abstract

The general purpose of normalization of EMG amplitude is to enable comparisons between participants, muscles, measurement sessions or electrode positions. Normalization is necessary to reduce the impact of differences in physiological and anatomical characteristics of muscles and surrounding tissues. Normalization of the EMG amplitude provides information about the magnitude of muscle activation relative to a reference value. It is essential to select an appropriate method for normalization with specific reference to how the EMG signal will be interpreted, and to consider how the normalized EMG amplitude may change when interpreting it under specific conditions. This matrix, developed by the Consensus for Experimental Design in Electromyography (CEDE) project, presents six approaches to EMG normalization: 1) Maximal voluntary contraction (MVC) in same task/context as the task of interest, 2) Standardized isometric MVC (which is not necessarily matched to the contraction type in the task of interest), 3) Standardized submaximal task (isometric/dynamic) that can be task-specific, 4) Peak/mean EMG amplitude in task, 5) Non-normalized, and 6) Maximal M-wave. General considerations for normalization, features that should be reported, definitions, and "pros and cons" of each normalization approach are presented first. This information is followed by recommendations for specific experimental contexts, along with an explanation of the factors that determine the suitability of a method, and frequently asked questions. This matrix is intended to help researchers when selecting, reporting and interpreting EMG amplitude data.

Key words: Electromyography; Muscle activation; Amplitude normalization; Consensus

1. Introduction

The estimation of the degree of muscle activation is one of the most common applications of electromyographic (EMG) recordings. Although the terms “muscle activation” and “EMG amplitude” are often used interchangeably, they represent different concepts. *Muscle activation* refers to the number of muscle fibers activated and their firing rates. *EMG amplitude* relates to the time-varying standard deviation of the EMG signal associated with the transmission of action potentials along the muscle fiber membranes. The raw interferential EMG signal is a noise-like signal. Although its amplitude is related to the level of muscle activation, the precise nature of the relationship is affected by many factors [Farina, Merletti, & Enoka, 2004, 2014; Raez, Hussain, & Mohd-Yasin, 2006]. To analyze and interpret EMG amplitude data, normalization is usually needed [Staudenmann, Roeleveld, Stegeman, & van Dieen, 2010].

The purpose of EMG amplitude normalization is to enable comparisons between participants, muscles, measurement sessions or electrode positions by accounting for features that would influence the amplitude of the EMG signal, and thus alter the nature of its relationship to muscle activation. These features include physiological and anatomical characteristics of muscles and surrounding tissues that could/would differ between muscles, study participants and testing sessions (e.g., distribution and number of fibers in the motor unit territories, orientation of the muscle fibers, thickness of the subcutaneous tissue layers, spatial organization of the innervation zone), and characteristics of the detection system (e.g., properties of the electrode-tissue interface, inter-electrode distance, orientation relative to muscle fibers) [Burden, 2010]. For any recording situation, it is generally not possible to quantify the contribution of each of these factors to variation in EMG amplitude. This makes it difficult to interpret the absolute value of the EMG signal amplitude. ~~For instance, when comparing the raw EMG amplitude signal of a muscle between participants, differences~~

~~observed between those individuals may be caused by variations in their subcutaneous tissue thickness and composition, or the manner in which the electrodes were placed with respect to the muscle of interest.~~

In principle, the normalized EMG amplitude value provides information about the degree of muscle activation present in a specific task context, expressed relative to a reference value used for normalization. Various normalization methods have been described [Burden, 2010; Merlo & Campanini, 2016], such as the reference to a maximal voluntary contraction (MVC), sub-maximal voluntary contraction, peak/mean during task, etc. Although normalization to an MVC is commonly used, because it is generally repeatable and provides a reference value that can be interpreted easily, i.e., relative to the maximum possible activation of the muscle [Bolgla & Uhl, 2007; Burden, 2010], this is not always possible and may not be the best method for some needed analyses [Hug & Tucker, 2017]. Although some methods have been reported as reliable [Albertus-Kajee, Tucker, Derman, Lamberts, & Lambert, 2011; Murley, Menz, Landorf, & Bird, 2010; Tabard-Fougere et al., 2018] and give similar values between sessions, this does not ensure that the normalized EMG amplitude value enables a valid comparison of the level of activation of a muscle(s) for a specific application or research question. It is important to consider whether the normalization method is both repeatable *and* valid, and suitable to answer the specific question being addressed with EMG. Accurate interpretation of EMG data depends on the appropriate selection of the amplitude normalization method and this should be well justified.

Several guidelines and recommendations provide guidance regarding methodological issues of EMG, such as the SENIAM project (European Recommendations for Surface Electromyography) [Hermens, Freriks, Disselhorst-Klug, & Rau, 2000], and the EMG reporting standards (International Society of Electrophysiology and Kinesiology) [Merletti, 2014]. These guidelines address some aspects of the EMG experimental design, but neither provides clear guidance for decision making with respect to the question being addressed by the application of EMG in research or clinical practice. This is important as different normalization methods may be appropriate/inappropriate for specific applications. Advice regarding the appropriateness of a normalization method for a specific context is not straight-forward. Although some recommendations are based on clear empirical evidence, many scenarios have not been addressed and recommendations depend on expert knowledge. Further, in some task contexts or in some participant groups (e.g., people with pain, children, etc.), the optimal method for EMG normalization may not necessarily be possible or practical. In such circumstances, decisions that are made concerning the means of analyzing and interpreting EMG amplitude may be guided usefully by recommendations from and, ideally consensus among, expert practitioners. The Consensus for Experimental Design in Electromyography (CEDE) project aims to provide expert consensus to guide decision-making in the recording, analysis, and interpretation of EMG [Hodges, 2019], and with specific reference to guidance for specific applications. Recommendations are presented as matrices that guide the application and interpretation of different salient features of EMG. The present CEDE matrix was developed to summarize recommendations for the normalization of EMG amplitude. The information presented in this document generally can be related to the rectified, smoothed EMG signal.

2. Methods

Details of the project, including the method for expert group selection, and the process for the development of the CEDE matrices have been described in detail elsewhere [Besomi et al., 2019; Hodges, 2019]. In brief, a three-step process was followed in preparation of this matrix: (1) Development of the draft content by a steering committee from the CEDE project; (2) General comments from CEDE team members with expertise in the topic; and (3) A Delphi process to reach consensus of the content. Participants of the Delphi process are co-authors. Approval for this project was obtained from the Human Research Ethics Committee of The University of Queensland, Australia.

2.1 Development of the draft content by the steering committee and CEDE project team

Draft content for the matrix was developed by the steering committee (MB, PWH) and CEDE project team members with expertise in this topic (EAC, JVD, FH, ML, RM, KS, TW). The content was prepared with consideration of the advantages and limitations of each EMG amplitude normalization method. Six methodological approaches to normalization of EMG amplitudes were considered in the matrix: 1) MVC in same task/context as the task of interest (with matched contraction type, muscle length/joint angle, and/or velocity), 2) Standardized isometric MVC (which is not matched to the contraction type, muscle length/joint angle, and/or velocity of the task), 3) Standardized submaximal task (isometric/dynamic) that can be task-specific, 4) Peak/mean EMG amplitude in task, 5) Non-normalized EMG amplitude, and 6) Maximal M-wave amplitude normalization. The matrix was reviewed by the nominated CEDE members to obtain feedback on the proposed design and content features of the initial draft. This process was followed by refinement of the content and further development before progressing to the Delphi process.

The overall format for this matrix was divided into six sections: general considerations for amplitude normalization, general features that should be reported, pros and cons of each method, common experimental contexts, and frequently asked questions. For each experimental context, a recommendation of the appropriateness of an EMG amplitude normalization method for a specific application was provided as “yes”, “caution”, “generally no”, or “no” (see Table 1 for definitions), along with an explanation.

2.2 Delphi process to reach consensus of the content

An online Delphi approach was used to reach consensus among experts. This approach is a widely accepted method to achieve consensus and is used as a decision-making method [Waggoner, Carline, & Durning, 2016]. The Delphi technique uses multiple rounds of questionnaires that can involve allocation of ratings and/or open-ended answers [von der Gracht, 2012]. In round one, the entire matrix was sent to the whole CEDE team (n=20) along with the instructions and timeline for completion. A reminder was emailed after two and four weeks. The same approach and timeline were used for the subsequent round. For the assessment of satisfaction level and agreement/disagreement among participants, a nine-point Likert scale was used [Fitch et al., 2001] that asked contributors to indicate that they considered that content was “appropriate” (score 7–9), “uncertain” (score 4–6) or “inappropriate” (score 1–3). Participants rated their agreement for each cell of the matrix and were invited to provide comments to highlight aspects that were not agreeable. Consensus was considered to be reached if >70% of contributors provided scores between 7–9 (appropriate) and <15% of contributors provided scores between 1–3 (inappropriate) [Williamson et al., 2012]. As a further criterion, an interquartile range (IQR) $\leq$ 2 units on a nine-unit scale was necessary to consider that consensus had been reached among Delphi panelists [von der Gracht, 2012]. For cells that reached consensus, any contributor’s comments that were recorded were considered and implemented as necessary.

Based on the results of round one, items with an insufficient consensus were refined by the steering committee by integrating feedback, and were re-sent to the experts who had provided ratings below 7 points. Changes or new information proposed by contributors were highlighted in the second-round questionnaire. All CEDE members reviewed the final document for endorsement and were included as authors. For this matrix, 20 experts participated in the Delphi process. The lead investigator (PH) and the coordinator (MB), who developed the draft matrix, did not participate in that process, but in addition to developing the initial content, they oversaw the project and collected/integrated all responses.

All data were entered and processed with Microsoft Excel. The number and percentage of participants rating each outcome as appropriate (score 7-9), uncertain (score 4-6) and inappropriate (score 1-3) were calculated, as well as the median and IQR for each item.

3. Results

From the 20 experts who agreed to participate in the Delphi process, 18 (80%) replied to the first-round questionnaire. Version 1 was composed of 19 items. After round one, nine sections were ranked with insufficient consensus. For round two, the nine sections were re-sent to experts who had rated an item lower than 7 points (n=13). Of those, 12 experts (92.3%) completed the second-round questionnaire. All sections reached consensus after this round. A summary of the results of the two rounds of the Delphi consensus process is presented in Appendix 1 and 2, respectively.

The EMG amplitude normalization matrix endorsed by the CEDE project team is presented in Table 2. A checklist (Table 3) is provided to guide and facilitate the reporting of EMG normalization based on the content of the matrix.

4. Discussion

The matrix developed in this Delphi consensus project represents a summary of recommendations of six methodological approaches for normalization of EMG amplitude. Ten experimental contexts that represent common questions that are asked in research and clinical application of EMG were included. For each context, a recommendation is provided with different levels of certainty.

Strengths and limitations of this consensus process have been described in detail elsewhere [Besomi et al., 2019]. In brief, the matrix represents a concise overview of common normalization methods and its application in different situations, as well as recommendations based on expert consensus opinion. Updates of this matrix will be needed as new empirical data emerges and as new methods become available. Because empirical data are not always available, some recommendations are based on logical and theoretical considerations.

Within the consensus process, there were some conflicting opinions between experts regarding the use of some normalization methods for specific applications. The greatest concern related to how to make decisions when the ideal method cannot be implemented. For instance, in participants with pain, it is commonly considered that participants may be unable or unwilling to perform a maximal effort. In that case, normalization to MVC is likely to be biased towards higher resulting values, variable and invalid. In some cases there is no method available to answer the research question (e.g., when participants cannot voluntarily activate a muscle [e.g., motor paralysis after cerebrovascular accident] or have difficulty activating the muscle [e.g., pelvic floor muscle activation in urinary incontinence, or pediatric population]). In those cases, where no ideal method is available, interpretation of the EMG amplitude may depend on the use of multiple sub-optimal methods, and consideration the convergence/divergence arising from these. When the task of interest *is* a maximum effort, normalization to MVC is not possible. In that case, non-normalized EMG amplitude may be considered with caution, but may require concurrent analysis of biomechanical parameters (e.g., physiological cross-sectional area and muscle fiber length) to interpret a difference or change within and between participants.

Some normalization methods are commonly used inappropriately, which leads to misleading interpretations and recommendations. For example, it has been proposed that normalization of EMG amplitude in a standardized submaximal task enables comparison between groups when an MVC is not possible. Unfortunately, the likelihood that participants in the groups perform the normalizing task in a manner that differs between groups, it renders this form of analysis invalid [Hug & Tucker, 2017]. If this method is used, this limitation upon the interpretation of data should be considered and discussed. Further, normalization to the peak or average amplitude in a task does not enable comparison of amplitude between groups or muscles. This method only reflects how the amplitude is distributed across the task and would remove differences between individuals with high and low activation.

A critical issue highlighted in this consensus process is that the ideal normalization method may be muscle- and task-dependent [Ball & Scurr, 2013]. EMG amplitude recorded during MVCs differs as a function of joint angle (i.e., muscle length) [Worrell et al., 2001] and shortening/lengthening velocity [Buckthorpe, Hannah, Pain, & Folland, 2012]. Normalization methods require careful consideration when dynamic tasks are being assessed.

5. Conclusion

This matrix presents recommendations for the selection of EMG normalization methods, developed by the CEDE project team. Its aim is to improve the quality of the reporting and interpretation of EMG amplitude data. This matrix includes six commonly used approaches for amplitude normalization along with their definitions, pros and cons, and consideration of the experimental contexts in which they are used commonly. This matrix does not replace formal training or education in EMG practice. Rather, it is intended for use as a reference when planning studies, and when reporting (and justifying) the decisions that are made in selecting EMG amplitude normalization methods. EMG normalization is a major issue that should be planned *before* data collection to ensure that the appropriate tasks are implemented and conducted, to enable valid methods of data analysis.

Statements

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Conflict of interest: None declared.

References

Albertus-Kajee, Y., Tucker, R., Derman, W., Lamberts, R. P., & Lambert, M. I. Alternative methods of normalising EMG during running. J Electromyogr Kinesiol., 21(4) (2011), pp.579-86.

Ball, N., & Scurr, J. Electromyography normalization methods for high-velocity muscle actions: review and recommendations. J Appl Biomech., 29(5) (2013), pp.600-8.

Besomi, M., Hodges, P. W., Van Dieën, J., Carson, R. G., Clancy, E. A., Disselhorst-Klug, C., . . . Wrigley, T. Consensus for experimental design in electromyography (CEDE) project: Electrode selection matrix. J Electromyogr Kinesiol., 48(2019), pp.128-44.

Bolgla, L. A., & Uhl, T. L. Reliability of electromyographic normalization methods for evaluating the hip musculature. J Electromyogr Kinesiol., 17(1) (2007), pp.102-11.

Buckthorpe, M. W., Hannah, R., Pain, T. G., & Folland, J. P. Reliability of neuromuscular measurements during explosive isometric contractions, with special reference to electromyography normalization techniques. Muscle and Nerve., 46(4) (2012),pp.566-76.

Burden, A. How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. J Electromyogr Kinesiol., 20(6) (2010), pp.1023-35.

Farina, D., Merletti, R., & Enoka, R. M. The extraction of neural strategies from the surface EMG. J Appl Physiol.,96(4) (2004), pp.1486-95.

Farina, D., Merletti, R., & Enoka, R. M. The extraction of neural strategies from the surface EMG: an update. J Appl Physiol., 117(11) (2014), pp.1215-30. doi:10.1152/japplphysiol.00162.2014

Fitch, K., Bernstein, S.J., Aguilar, M.D., Burnand, B., LaCalle, J.R., Lazaro, P., van het Loo, M., McDonnell, J., Kahan, JP. The Rand/UCLA appropriateness method user's manual. Santa Monica, CA: RAND Corporation; 2001.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol., 10(5) (2000), pp.361-74.

Hodges, P. W. Editorial: Consensus for Experimental Design in Electromyography (CEDE) project. J Electromyogr Kinesiol., 50 (2019), pp.102343.

Hug, F., & Tucker, K. Surface Electromyography to Study Muscle Coordination. In B. Müller, S. I. Wolf, G.-P. Brueggemann, Z. Deng, A. McIntosh, F. Miller, & W. S. Selbie (Eds.). Handbook of Human Motion (2017), pp. 1-21. Cham: Springer International Publishing.

Merletti, R. Standards for Reporting EMG Data. J Electromyogr Kinesiol., 24(2) (2014), pp.I-II.

Merlo, A., Campanini, I. Applications in Movement and Gait Analysis. In: Merletti, R., Farina, D., editors. Surface Electromyography: Physiology, Engineering, and Applications. (2016), Chapter 16: p.440-59.

Murley, G. S., Menz, H. B., Landorf, K. B., & Bird, A. R. Reliability of lower limb electromyography during overground walking: a comparison of maximal- and sub-maximal normalisation techniques. J Biomech., 43(4) (2010), pp.749-56.

Raez, M. B. I., Hussain, M. S., & Mohd-Yasin, F. Techniques of EMG signal analysis: detection, processing, classification and applications. Biol Proced Online., 8 (2006), pp.11-35.

Staudenmann, D., Roeleveld, K., Stegeman, D. F., & van Dieen, J. H. Methodological aspects of SEMG recordings for force estimation--a tutorial and review. J Electromyogr Kinesiol., 20(3) (2010), pp.375-87.

Tabard-Fougere, A., Rose-Dulcina, K., Pittet, V., Dayer, R., Vuillerme, N., & Armand, S. EMG normalization method based on grade 3 of manual muscle testing: Within- and between-day reliability of normalization tasks and application to gait analysis. Gait Posture., 60 (2018), pp.6-12.

von der Gracht, H. A. Consensus measurement in Delphi studies: Review and implications for future quality assurance. Technol Forecast Soc., 79(8) (2012), pp.1525-36.

Waggoner, J., Carline, J. D., & Durning, S. J. Is There a Consensus on Consensus Methodology? Descriptions and Recommendations for Future Consensus Research. Acad Med., 91(5) (2016), pp.663-8.

Williamson, P. R., Altman, D. G., Blazeby, J. M., Clarke, M., Devane, D., Gargon, E., & Tugwell, P. Developing core outcome sets for clinical trials: issues to consider. Trials., 13(1) (2012), pp.132.

Worrell, T. W., Karst, G., Adamczyk, D., Moore, R., Stanley, C., Steimel, B., & Steimel, S. Influence of joint position on electromyographic and torque generation during maximal voluntary isometric contractions of the hamstrings and gluteus maximus muscles. J Orthop Sports Phys Ther., 31(12) (2001), pp.730-40.

Table 1

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Table 3

Appendix 1

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Author biography

Manuela Besomi is a PhD candidate at The University of Queensland. She received her Bachelor degree in Physiotherapy (Universidad del Desarrollo, Chile) and completed her MPhil degree in Clinical Epidemiology at Universidad de La Frontera (Chile) in 2016. Her current PhD project involves shear wave elastography, electromyography, biomechanics and physical tests to understand whether novice runners with iliotibial band syndrome and patellofemoral pain move and use muscles differently than people without the condition.

Conflict of Interest and Authorship Conformation Form

- All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

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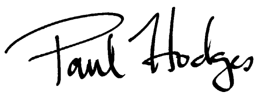

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