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REVIEW

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Signal acquisition and analysis of ambulatory electromyographic recordings for the assessment of sleep bruxism: A scoping review

Magdalini Thymi[1] | Frank Lobbezoo[1] | Ghizlane Aarab[1] | Jari Ahlberg[2] | Kazuyoshi Baba[3] | Maria Clotilde Carra[4] | Luigi M. Gallo[5] | Antoon De Laat[6,7,8] | Daniele Manfredini[9] | Gilles Lavigne[10,11] | Peter Svensson[12,13]

[1]Department of Orofacial Pain and Dysfunction, Academic Centre for Dentistry Amsterdam, University of Amsterdam and Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

[2]Department of Oral and Maxillofacial Diseases, University of Helsinki, Helsinki, Finland

[3]Department of Prosthodontics, Showa University School of Dentistry, Ohta-ku, Japan

[4]UFR of Odontology Garanciere, Université de Paris and Service of Odontology, Rothschild Hospital (AP-HP), Paris, France

[5]Clinic of Masticatory Disorders, Center of Dental Medicine, University of Zurich, Zurich, Switzerland

[6]Department of Oral Health Sciences, Leuven, Belgium

[7]Department of Oral and Maxillofacial Surgery, University Hospitals Leuven, Leuven, Belgium

[8]Department of Dentistry, University Hospital, Leuven, Belgium

[9]Department of Biomedical Technologies, School of Dentistry, University of Siena, Siena, Italy

[10]Faculty of Dental Medicine, Université de Montréal, Montreal, QC, Canada

[11]CIUSSS Nord Ile de Montreal, Center for Advance Research in Sleep Medicine & Stomatology, CHUM, Montreal, QC, Canada

[12]Section of Orofacial Pain and Jaw Function, Department of Dentistry and Oral Health, Aarhus Universitet Tandlageskolen, Aarhus, Denmark

[13]Faculty of Odontology, Malmø University, Malmø, Sweden

Abstract

Background: Ambulatory electromyographic (EMG) devices are increasingly being used in sleep bruxism studies. EMG signal acquisition, analysis and scoring methods vary between studies. This may impact comparability of studies and the assessment of sleep bruxism in patients.

Objectives: (a) To provide an overview of EMG signal acquisition and analysis methods of recordings from limited-channel ambulatory EMG devices for the assessment of sleep bruxism; and (b) to provide an overview of outcome measures used in sleep bruxism literature utilising such devices.

Method: A scoping review of the literature was performed. Online databases PubMed and Semantics Scholar were searched for studies published in English until 7 October 2020. Data on five categories were extracted: recording hardware, recording logistics, signal acquisition, signal analysis and sleep bruxism outcomes.

Results: Seventy-eight studies were included, published between 1977 and 2020. Recording hardware was generally well described. Reports of participant instructions in device handling and of dealing with failed recordings were often lacking. Basic elements of signal acquisition, for example amplifications factors, impedance and bandpass settings, and signal analysis, for example rectification, signal processing and additional filtering, were underreported. Extensive variability was found for thresholds used to characterise sleep bruxism events. Sleep bruxism outcomes varied, but typically represented frequency, duration and/or intensity of masticatory muscle activity (MMA).

Conclusion: Adequate and standardised reporting of recording procedures is highly recommended. In future studies utilising ambulatory EMG devices, the focus may need to shift from the concept of scoring sleep bruxism events to that of scoring the whole spectrum of MMA.

Correspondence
Magdalini Thymi, Academisch Centrum Tandheelkunde Amsterdam, Amsterdam, The Netherlands.
Email: m.thymi@acta.nl

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ambulatory electromyographic device, limited channel device, masticatory muscle activity, sleep bruxism, surface electromyography

1 | INTRODUCTION

Sleep bruxism is accompanied by masticatory muscle activity (MMA) during sleep, and its definition has received much attention over the years.[1] The most recent definition states that sleep bruxism is a masticatory muscle activity that is characterised as rhythmic (phasic) or non-rhythmic (tonic) muscle contractions.[2] The term 'rhythmic' has extensively been used in the past to indicate MMA during sleep that is characterised by a repetitive pattern.[3-6] Rhythmic masticatory muscle activity (RMMA) has been considered the cardinal feature of sleep bruxism on electromyographic (EMG) traces derived from polysomnographic audio-video (PSG-AV) sleep laboratory studies.[3-5] In such studies, RMMA is distinguished from other types of MMA, more specifically from orofacial activities (OFAs; ie MMAs *without* characteristic patterns, such as swallowing, yawning and coughing) and from oro-motor activities (OMAs; ie MMAs that are part of major movements, including head, neck or body movements).[3,7,8] Currently, sleep bruxism research is shifting towards adopting the more general term MMA, instead of RMMA.[9,10] This shift is driven by technical advancements and accumulating evidence in the field of ambulatory EMG recorders that are increasingly being used in sleep bruxism studies (eg[11-13]). Their development is evolving, for example in terms of reduced size[14] and compatibility with other technologies, such as smartphone applications.[15] They allow for assessment of the whole spectrum of MMA, but are less able to discriminate between RMMA, OMA and OFA, compared to PSG-AV.[3] Indeed, ambulatory EMG devices are known to overestimate sleep bruxism activity, compared to the gold standard, viz. PSG-AV recordings.[16] However, they have obvious benefits compared to PSG-AV, regarding costs and simplicity, and are therefore more pragmatic and important alternatives for the study of sleep bruxism on a larger scale.[17] Most importantly though, the shift towards assessment of the whole spectrum of MMA, instead of the more restricted RMMA, is driven by its clinical relevance.[9] It is plausible that clinical health outcomes, for example masticatory muscle pain, are related to EMG outcomes including, but not limited to, RMMA. Features of MMA, such as background EMG activity,[18] intensity and timing,[19,20] amplitude of activity[21] and variability of activity over time,[22] have been studied in relation to musculoskeletal signs and symptoms (for a comprehensive overview, see[23]). The importance of addressing the continuum of MMA in order to understand its relation to specific clinical outcomes has been discussed extensively in previous publications.[2,9,10,24,25]

Instrumental, assessment of MMA with the use of EMG, with or without positive self-report and/or positive clinical inspection is needed to establish a 'definite' sleep bruxism diagnosis, according to the current bruxism diagnostic grading system.[2,10] The choice of criteria to score sleep bruxism on EMG recordings is a matter of ongoing discussion and research.[2,9]

EMG recordings can be derived from attended or unattended (ie type 1 or type 2), PSG recordings, as well as limited-channel, portable (ie type 3 and 4) EMG recorders[26-28] (Table 1). Once acquired, the EMG signal is scored to provide outcomes of MMA.

EMG bursts are widely used as the basic elements of sleep bruxism outcome measures.[29] Various thresholds above which EMG activity is defined as a bruxism-related burst have been used in literature, such as percentages of the maximum voluntary contraction (MVC) level,[11,29-32] multiplications of the baseline EMG activity[33-36] and recognition of a specific EMG pattern.[37] It is conceivable that the use of different thresholds for the assessment of the same EMG recording will lead to differences in the scoring of sleep bruxism outcomes, thus rendering comparison of studies difficult, if not impossible. Moreover, it may be hypothesised that the assessment of sleep bruxism in the clinic is

TABLE 1 Types of sleep recording devices

Type	Descriptiony[26,27]	Examples[a]
Type 1	Full attended polysomnography (≥7 channels) in a laboratory setting	
Type 2	Full unattended polysomnography (≥7 channels)	
Type 3	Limited-channel devices (usually 4–7 channels)	Bruxoff (3 channels: 2 for bilateral masseter, 1 for ECG) TEAC-HR-10 J (3 channels: 1 for masseter, 1 respiratory, 1 for ECG) Myomonitor (4 channels: 2 for bilateral masseter, 2 for bilateral temporalis)
Type 4	1–2 channels	Pro-comp INFINITI (2 channels: 1 for masseter, 1 for ECG) EMG-021/025, KTR2302B (2 channels for bilateral masseter) Grindcare (1 channel for temporalis)

Abbreviation: ECG, electrocardiography.

[a]Examples of electromyographic recorders included in this review.

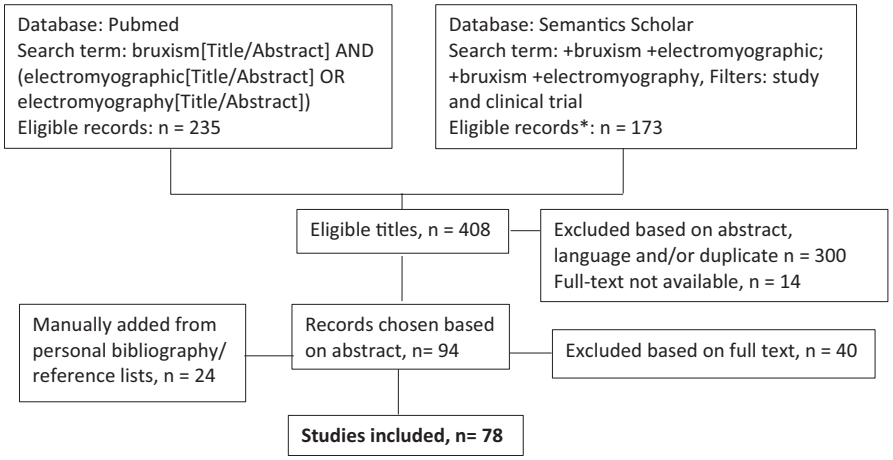

FIGURE 1 Search terms and inclusion flowchart

impacted, since a patient may receive a different sleep bruxism diagnosis, depending on the threshold used to score an EMG recording.

After being scored, EMG bursts may be used to construct other measures of sleep bruxism events, such as sleep bruxism episodes.[29] To this end, the criteria from Reding,[6] which were adapted by Ware and Rugh,[38] and proposed as sleep bruxism criteria by Lavigne et al[29] (hereafter referred to as SB/research criteria) are currently widely used to define three types of episodes: phasic, tonic and mixed.[29] These criteria are based on EMG recordings as a part of PSG-AV sleep laboratory assessments and have been transferred and used for the scoring of ambulatory EMG signals (eg[12,39]), despite concerns regarding the validity of using these criteria in the absence of audiovisual recordings.[4,40] Furthermore, indices consisting of the number of EMG bursts or episodes per hour of sleep are commonly calculated.[11,22,29,32,37] Other indices may, amongst others, involve the number of EMG bursts or episodes per recording,[11,22] the total duration of those activities per hour of sleep,[11,32] the EMG area under the curve (AUC) per hour of sleep,[32] magnitude of muscle work over time,[19] the variability of activity over time[41,42] or the duration of the intervals between consecutive episodes.[20] Thus, a substantial variation in the expression of sleep bruxism EMG outcomes exists, without standardisation so far.

Besides variation in scoring of bruxism outcomes on an EMG signal, significant variation may also arise in the acquisition of the EMG signal itself, due to differences in technical specifications of EMG devices, for example in terms of electrode material and size, interelectrode distance, accepted impedance, amplification and filtering, and further processing of the EMG signal.[43,44] Improper technical characteristics may lead to the acquisition of unreliable EMG signal[43] and may further complicate comparison between studies. To this end, it has been recommended that studies adequately report on the technical aspects of EMG recordings,[45] but unfortunately this is not always the case.[46]

Ambulatory EMG devices are indeed promising tools for future large-scale studies of sleep bruxism, and MMA during sleep in general.[15,47] A substantial number of different devices are, or have been, available for research and/or commercial purposes. The validity of ambulatory EMG devices, compared to PSG recordings, has been addressed in previous literature reviews (see[16,48,49]). However, a comprehensive overview of how sleep bruxism outcomes have been scored in studies uses ambulatory EMG recordings, and the technical aspects of these studies are lacking. Ideally, ambulatory EMG devices should allow for an accurate and uniform way to acquire EMG recordings and score EMG features of sleep bruxism in the natural environment of individuals. As a first step towards this goal, this paper was designed: (a) to provide an overview of EMG signal acquisition and analysis methods of recordings from type 4 ambulatory EMG devices for the assessment of sleep bruxism; and (b) to provide an overview of outcome measures used so far in sleep bruxism literature utilising such ambulatory EMG devices. The ultimate goal of this study is to provide information that can facilitate further development of a standardised tool for the assessment of sleep bruxism,[10] including protocols for recording, data acquisition and scoring that should be ideally applicable to all devices eventually used to study sleep bruxism. This would facilitate comparability of studies in the research setting, and the development and application of proper devices for use in clinical settings.

2 | MATERIALS AND METHODS

A scoping review of the literature was performed.[50,51] Scoping reviews are specific types of reviews that allow structured mapping of evidence on a broad research question, and identification of gaps in existing literature.[50,51] They can also be used to identify the potential scope of a subsequent systematic review.[51] Scoping reviews differ from systematic reviews mainly in that they provide an overview of all existing literature on a particular topic, without quality assessment of the data.[50,51] To be suitable for inclusion in this scoping review, a study should fulfil the following criteria: (1) clinical study with the use of an ambulatory type 3 or 4 EMG recorder for the assessment of sleep bruxism, and (2) reports sleep bruxism outcomes. Only studies that reported data were included, viz. publications of study protocols, were excluded. Studies with type 1 or 2 devices[27] were also excluded. Online databases PubMed and Semantics Scholar were searched for studies published in English

until 7 October 2020. Search terms and the inclusion flowchart are presented in Figure 1. Risk of bias assessment was not applicable for this review,[50,51] since the aim was to provide a comprehensive overview of all signal acquisition and scoring methods in the sleep bruxism literature. Data from the included studies were extracted into a worksheet. Table 2 provides an overview of the assessed variables. The search and inclusion procedures as well as data extraction were performed by one author (MT). When authors

TABLE 2 Extracted variables from included studies

Category	Variable	Description of what was assessed
General study information	First author, year, journal	First author, year, journal
	Study type	For example, cross-sectional, case-control
	Population	Adults/children
Recording hardware	Description of EMG device	Authors' description of type of EMG device
	Commercial name of EMG device	Commercial name, description and/or manufacturer of EMG device
	Electrode type	Description of electrode
	Wireless electrode	Yes/no
	Number of channels	Number and site of channels
	Muscles	Which masticatory muscles were used for signal acquisition
	Picture of device	Present in publication; yes/no
	Use of additional instrumental methods to assess bruxism	For example, electrocardiographic activity, audiovisual recordings
Recording logistics	Number of recording nights (not including the adaptation night)	Total number and, if applicable, number of recording sets (eg within 3 weeks, 3 sets of 4 recording nights)
	Adaptation night before scoring	Yes/no
	Setting	Home/sleep laboratory
	Participant instructions device and electrode handling	How were participants instructed on using the device and handling the electrode
	Participant instructions device set-up	If applicable, how were participants instructed to set-up the device (eg performing MVC)
	Electrode placement	By participant of investigator
	How are failures dealt with	Which action followed if acquisition of the recording failed
Signal acquisition	Amplification factor	How many times was the signal amplified
	Impedance measurement	What data are provided on amplifier input and/or skin impedance
	Bandpass settings	What was the frequency range of the signal acquisition
	Notch filter	Frequency of additional notch filter
	A/D resolution	What was the resolution of the A/D converter
	Sampling rate	At which frequency was the signal sampled
Signal analysis	Device output	Raw EMG signal/scored activity (viz. activity which was scored after automatic analysis of the EMG signal inside the EMG device)
	Definition of analysis time	Which part of the signal was analysed
	EMG scoring software	Commercial name
	Rectification	Was the signal rectified
	Processing	Was the signal further processed, if yes, how
	Additional filtering	Was there any additional filtering performed in the analysis process
	Threshold for EMG scoring	Which threshold was used to score EMG events
	Definition of event	How was an event defined
Sleep bruxism outcomes	Use of RMMA term as outcome variable	Yes/no
	Diagnosis of 'sleep bruxer' through cut-off criteria	Were cut-off criteria used to define a bruxer, and if so, which
	Reported outcomes	Which sleep bruxism outcomes are reported

Abbreviations: A/D, analog-to-digital; EMG, electromyographic; MVC, maximum voluntary contraction.

referred to another study, and the relevant information could indeed be found in the other study, it is reported as 'refers to other'. It was not the purpose of the review to provide a thorough description of all technical specifications of EMG recordings, but rather, to limit itself to the reported items of the International Society of Electrophysiology and Kinesiology (ISEK).[45]

3 | RESULTS

3.1 | General study information

Seventy-eight studies were included in this review (Figure 1). They were published between 1977 and 2020, with almost half (56%) having been published from the year 2013 on. Seventy-six studies included adult populations. Study type characteristics are presented in Table 3.

3.2 | Recording hardware

Various terms were used to describe the ambulatory EMG recorders, the most common being 'portable EMG device'[32,37,52-57] (n = 8; 10%), followed by 'portable EMG recorder'[58-61] and 'portable single-channel EMG device'[33,62-64] (for each n = 4; 5%). All but two[59,65] studies provided a description of the devices' components and/or information on their commercial names and/or manufacturers. Devices used more commonly were the 'Grindcare' in different versions[22,31,37,52,56,57,61-64,66-70] (n = 15; 19%), followed by the 'Bitestrip'[13,71-81] (n = 12; 15%), and the 'Bruxoff'[30,82-89] (n = 9; 12%) device (see online Appendix for overview). Pictures of devices were provided in 18 (23%) of the studies.[11,12,14,19,33,37,55,58,59,66,67,83,84,90-94] Eleven studies used additional instrumental methods to assess sleep bruxism, viz. audio recordings[54] (n = 1), video recordings[95] (n=1), audiovisual recordings[96,97] (n = 2) and electrocardiographic (ECG) activity[82-87,92,98] (n = 8, 10%).

Most studies (n = 44; 57%) utilised a single-channel assembly,[13,14,22,31,37,39,52,54,56,57,60-64,66-81,90,91,95-97,99-107] and two and three channels were utilised in 13 (17%)[11,12,32,33,52,59,92-94,108-111] and 15 (19%)[19,30,82-88,98,112-116] studies, respectively, while two[53,117] studies used a four-channel assembly (see online appendix for specifications of channel assemblies). The most prevalent recording site was the masseter muscle in 45 (58%) studies,[11-14,30,32,33,39,54,65,72-88,90-92,94,98-111,117,118] followed by the temporalis muscle in 21 (27%) studies,[15,22,31,37,52,56,57,60-64,66,67,69-71,93,95-97] and both muscles in 10 studies.[19,30,53,59,112-117] One study[119] did not provide details on the recording site, but referred to another publication instead.

Electrodes connected to the devices through wires were used in 52 (67%) studies,[11,12,19,22,30-33,39,53,54,56,57,59-70,82-88,92-100,102,105-112,117,118] while 17 (22%) studies[13,14,37,52,55,71-76,78-81,90,91] utilised wireless electrodes (see online appendix for overview of electrode descriptions). Four studies[101,113,116,119] did not describe the type of electrode, but referred the reader to another publication with description.

TABLE 3 Overview of study types

Study type	n	First author & year
Algorithm development/cross-sectional	2	Čadová 2014, Ikeda 1996
Before-after interventional	9	Castro Mattia 2018, Clark 1981, Kardachi 1977, Manfredini 2018, Needham 2013, Raphael 2013, Rugh 1981, Saueressig 2010, Zhou 2016
Case-control	18	Ahlberg 2008, Camara-Souza 2018, Iwasaki 2015, Jonsgar 2015, Karakoulaki 2015, Kato 2018, Minakuchi 2014, Miyawaki 2003, Mude 2017, Nitschke 2011, Ohlmann 2018, Ono 2008, Palinkas 2019, Schmitter 2015, Shedden Mora 2012, Suganuma 2007, Wei 2017, Yachida 2012
Controlled interventional	2	Rugh 1984 & 1989
Cross-sectional	19	Baba 2005, Clarke 1984 & 1984, Hammoudi 2019, Khawaja 2015, Manfredini 2011, 2016 & 2019, Matsuda 2016, Minakuchi 2016, Miyawaki 2004, Mizumori 2013, Murakami 2014, Nagamatsu-Sakaguchi 2017, Ohlmann 2020, Po 2013, Takaoka 2017, Thymi 2019, Yamaguchi 2012
Device development/case report	1	Yamaguchi 2018
Device development/cross-sectional	2	Haketa 2003, Stock 1983
Device development/case-control	1	Sakagami 2002
Diagnostic validity	7	Castroflorio 2014 & 2015, Gallo 1997, Maeta 2019, Mainieri 2012, Shochat 2007, Stuginski-Parbosa 2015
Epidemiological	2	Gallo 1999, Minakuchi 2012
Prospective cohort	1	Thymi 2020
Randomised controlled trial	13	Abekura 2008, Baad-Hansen 2007, Carvalho Bortoletto 2016, Conti 2014, Harada 2006, Jadidi 2008 & 2013, Lee 2010, Matsumoto 2015, Mohamed 1997, Saito- Murakami 2020, Shedden Mora 2013, Shimada 2019
Reliability	1	Deregibus 2014

Abbreviation: n, number of studies.

3.3 | Recording logistics

Twenty-five (32%) studies[12,14,33,54,56,73,78-80,82,83,85,88,90-92,94,96,97,99,100,105,108,117] based their analyses on single-night recordings, and two studies did not clearly describe the number of recordings,[76,115] while all other studies (n = 51; 65%)[11,13,15,19,22,31,32,37,39,52,53,57,59-67,69-72,74,75,77,84,86,87,89,93,95,98,101-104,106,107,109-114,116,118,119] performed multiple night recordings, with a maximum of 70 recordings per participant[67] (see online appendix for overview of the number of recording nights per study). An adaptation night prior to scoring, that is a recording night which allowed participants to get accustomed to the recording procedure, the data of which were not used for further analyses, was performed in 17 (22%) of the studies.[9,11,30,32,39,54,80,82,83,85,90-92,96,97,108,109] In the vast majority (n = 63; 82%) of studies, recordings were performed at the home setting,[11-14,19,22,30-32,37,39,52-54,56,57,59-64,66-70,72-77,79,82-88,91-94,96-98,100-102,106-110,117,119] with four studies situated in a laboratory[33,78,80,90] and 11 studies not clearly describing the setting.[71,81,89,95,99,105,111-114,116] Placement of the electrode on the skin was performed by participants themselves in almost half of studies (n = 40; 52%).[11-14,19,22,31,37,39,52,53,56,57,59,60,63,64,66-70,73-76,82,84,92-94,102,105,106,109,118] In one study on children, the electrode was placed by the caregiver,[71] while in six studies the procedure was performed by the study investigators.[33,54,100,101,110,117] The description of who placed the electrode was unclear for 29 (37%) studies,[30,32,61,62,72,77-81,83,85-87,89-91,95-99,108,111-116] while two studies referred to another publication for a description.[9,119]

Over half of the studies (n = 44; 56%)[11-14,19,22,30,31,37,39,52,53,56,59,60,63-66,69-71,73-76,80,82,84,87,92-95,102,105,107,109,110,114,117,119] reported that instructions were given to participants on how to handle the device and/or its components. Reports varied from brief statements, for example 'subjects received instruction on how to handle the device as well as the placement of the electrodes',[39] to more detailed descriptions, for example 'participants were … instructed in its usage in a home environment using a mirror and an instruction manual over 15 min by two trained instructors'.[76] Thirty-two studies (41%)[30,32,57,61,62,67,72,77-81,83,85-87,89-91,95-99,103,104,106,108,111,112,115,118] did not describe whether participants were given instructions on device handling, while for five studies[33,54,100,101,110] this information was not applicable, since the devices were mounted by the study investigators. As for set-up procedures, for example performing an MVC at the start of the recording, these were described for 37 (47%) of the studies,[11,14,22,30,31,37,39,52-54,56,61,62,67-69,73,77,78,80-84,90,91,95,96,98,100,101,107-111,117] while the remaining 41 (53%) studies did not describe such procedures.

Certain actions were reported in case a recording failed; that is, recorded data were partially or completely insufficient for analysis. Additional instructions were given to participants in two studies,[11,109] while nine studies reported repeating failed recordings.[32,39,69,73,77,101,109,110,114] Nine studies[11,37,39,52,92,93,95,99,107] reported removing artefacts, for example arising from high noise levels, from the raw EMG signal prior to signal analysis. Recordings were completely discarded from further analysis in case of failure in 15 (19%) studies.[22,54,56,57,62-64,68,70,76,95,102,110,117,119] 'Noisy signals were identified and excluded' in one study, without further specification of the term 'noisy signals', that is reference to artefact or complete recording.[59] One study [14] reported evaluating signal quality and not finding artefacts, while another study[108] reported evaluating the signal for artefact, but without mentioning how these were dealt with. The remaining 45 (58%) studies did not report how failures were evaluated and/or dealt with.

3.4 | Signal acquisition

The amplification factor of the signal during acquisition was described in only 19 (24%) studies[14,19,22,30,31,33,59-61,70,83,84,90,91,106,108,110,120] (Table 4). Different amplification factors were used for different devices, ranging from 250[90,115] to 50 000 times.[93]

Reports on impedance conditions were scarcer (Table 4). Five studies reported an amplifier input impedance of 10 kΩ,[115] >2[106] and 250 MΩ.[19,59,60] Another five studies reported on skin impedance measurements, that is <2[99,110] and <10 kΩ.[37,52,69]

The frequency range of signal sampling, that is bandpass settings, was described in 27 studies (35%)[14,19,22,30-33,37,52,54,59-61,67,70,83,84,90,93,95,100,102,106,108,110,111,115] (Table 4). Similar to the amplification factor, bandpass settings varied between different devices. As for additional notch filtering, two studies reported a 50 Hz notch filter,[95,102] while another three studies reported a 60 Hz notch filter during analysis of the signal[54,100,106] (Table 4).

The resolution of the analog voltage to digital (A/D) signal converter was reported in 13 (17%) studies[11,14,30,33,67,83,84,90,99,108,110,115,117] and ranged between 8 bit[83,84,99,115] and 16 bit (Table 4). Data on sampling rates were provided in 31 (40%) studies[11,14,19,30,32,33,37,39,52-54,59,67,83,84,91,92,95-97,99,102,105,107-112,115,117] (Table 4). Frequencies varied between 10 Hz[102] and 22050 Hz,[54] with the majority of studies utilising frequencies of approximately 1000[14,33,53,91,92,96,97,99,107,110,112,117] and 2000 Hz[19,32,37,52,59,67,108,109,111] (n = 12 and 9, respectively).

3.5 | Signal analysis

Analysis of the acquired signal was performed either automatically by the EMG device, or as a separate step, after EMG data were transferred from the device to a computer. In the first case, built-in software analysed and scored the signal, and thus, the output of the EMG device was scored activity, which was reported in 30 (38%) studies.[13,22,31,56,61,62,64-67,69,71-81,88,93,103,104,113-116] In 30 (38%) studies,[19,30,33,39,53,54,57,59,60,68,70,83,84,90-92,96-98,100-102,107-109,111,117-119] the output of the EMG device was raw EMG activity. In seven studies, the signal was stored in the device after undergoing some form of processing, for example rectification,[32,95,99,110,112] or if certain conditions were met, for example only recording EMG activity with an amplitude >5 μV. [11] Studies performing analysis of

TABLE 4 EMG signal acquisition characteristics

	Outcome	*n*	First author & year
Amplification factor	250×	2	Maeda, 2019, Stock 1983
	256×	1	Yamaguchi 2018
	500×	2	Matsuda, 2016, Yamaguchi 2012
	800×	4	Stuginski-Barbosa 2015, Thymi 2019, Yachida 2012, Zhou 2016
	2000×	1	Mohamed 1997
	3590×	1	Gallo 1999
	4300×	3	Castroflorio 2014 & 2015, Deregibus 2014
	5000×	3	Iwasaki 2015, Khawaja 2015, Wei 2017
	8692×	1	Po 2013
	50 000×	1	Sakagami 2002
	Amplified signal, factor not described	13	Abekura 2008, Baad-Hansen 2007, Baba 2005, Čadová 2014, Haketa 2003, Ikeda 1996, Karakoulaki 2015, Lee 2010, Manfredini 2011, Minakuchi 2012 & 2014, Nagamatsu-Sakaguchi 2017, Shedden Mora 2012
	Refers to other publication	12	Clarke 1984 & 1984, Gallo 1997, Kardachi 1977, Kato 2018, Manfredini 2016, 2018 & 2019, Nitschke 2011, Rugh 1989, Shedden Mora 2012, Thymi 2020
	Not described	34	Ahlberg 2008, Camara-Souza 2018, Carvalho Bortoletto 2016, Castro Mattia 2018, Clark 1981, Conti 2014, Harada 2006, Hammoudi 2019, Jadidi 2008 & 2013, Jonsgar 2015, Mainieri 2012, Matsumoto 2015, Minakuchi 2016, Miyawaki 2003 & 2004, Mizumori 2013, Mude 2017, Murakami 2014, Needham 2013, Ohlmann 2018 & 2020, Ono 2008, Palinkas 2019, Raphael 2013, Rugh 1981 & 1984, Saito-Murakami 2020, Saueressig 2010, Schmitter 2015, Shimada 2019, Shochat 2007, Suganuma 2007, Takaoka 2017
Input and/or skin impedance	Amplifier 10 kΩ	1	Stock 1983
	Amplifier >2 MΩ	1	Mohamed 1997
	Amplifier 250 MΩ	3	Iwasaki 2015, Khawaja 2015, Wei 2017
	Skin <2 kΩ	2	Gallo, 1997 & 1999
	Skin <10 kΩ	3	Jadidi 2008 & 2013, Takaoka 2017
	Refers to other publication	5	Clarke 1984 & 1984, Kardachi 1977, Nitschke 2011, Rugh 1989
	Not described	63	Abekura 2008, Ahlberg 2008, Baad-Hansen 2007, Baba 2005, Čadová 2014, Camara-Souza 2018, Carvalho Bortoletto 2016, Castro Mattia 2018, Castroflorio 2014 & 2015, Clark 1981, Conti 2014, Deregibus 2014, Haketa 2003, Hammoudi 2019, Harada 2006, Ikeda 1996, Jonsgar 2015, Karakoulaki 2015, Kato 2018, Lee 2010, Maeda 2019, Mainieri 2012, Manfredini 2011, 2016, 2018 & 2019, Matsuda 2016, Matsumoto 2015, Minakuchi 2012, 2014 & 2016, Miyawaki 2003 & 2004, Mizumori 2013, Mude 2017, Murakami 2014, Nagamatsu-Sakaguchi 2017, Needham 2013, Ohlmann 2018 & 2020, Ono 2008, Palinkas 2019, Po 2013, Raphael 2013, Rugh 1981 & 1984, Saito-Murakami 2020, Sakagami 2010, Saueressig 2010, Schmitter 2015, Shedden Mora 2012 & 2013, Shimada 2019, Shochat 2007, Stuginski-Barbosa 2015, Suganuma 2007, Thymi 2019 & 2020, Yachida 2012, Yamaguchi 2012 & 2018, Zhou 2016
Bandpass settings	5–500 Hz	1	Maeda 2019
	5.3–450 Hz	1	Saito-Murakami 2020
	10–400 Hz	3	Castroflorio 2014 & 2015, Deregibus 2014
	10–500 Hz	3	Shedden Mora 2012, Stock 1983, Yamaguchi 2012
	10–1000 Hz	2	Mude 2017, Kato 2018
	20–? Hz	1	Yamaguchi 2018
	20–500 Hz	1	Baad-Hansen 2007
	20–600 Hz	2	Jadidi 2008 & 2013
	20–1000 Hz	3	Iwasaki 2015, Khawaja 2015, Wei 2017

(Continues)

TABLE 4 (Continued)

	Outcome	*n*	First author & year
	50–500 Hz	2	Čadová 2014, Gallo 1999
	70–500 Hz	1	Po 2013
	100–200 Hz	1	Sakagami 2010
	100–310 Hz	1	Mohamed 1997
	250–600 Hz	1	Raphael 2013
	250–610 Hz	3	Stuginski-Barbosa 2015, Thymi 2019, Yachida 2012
	251–610 Hz	1	Zhou 2016
	Refers to other publication	9	Clarke 1984 & 1984, Kardachi 1977, Manfredini 2016, 2018 & 2019, Nitschke 2011, Rugh 1989, Shedden Mora 2013, Thymi 2020
	Not described	42	Abekura 2008, Ahlberg 2008, Baba 2005, Camara-Souza 2018, Carvalho Bortoletto 2016, Castro Mattia 2018, Clark 1981, Conti 2014, Gallo 1997, Haketa 2003, Hammoudi 2019, Harada 2006, Ikeda 1996, Jonsgar 2015, Karakoulaki 2015, Lee 2010,, Mainieri 2012, Manfredini 2011, Matsuda 2016, Matsumoto 2015, Minakuchi 2012, 2014 & 2016, Miyawaki 2003 & 2004, Mizumori 2013, Murakami 2014, Nagamatsu-Sakaguchi 2017, Needham 2013, Ohlmann 2018 & 2020, Ono 2008, Palinkas 2019, Rugh 1981 & 1984, Saueressig 2010, Schmitter 2015, Shimada 2019, Shochat 2007, Suganuma 2007, Takaoka 2017,
Notch filter	50 Hz	2	Saito-Murakami 2020, Shedden Mora 2012
	60 Hz	3	Kato 2018, Mohamed 1997, Mude 2017
	Refers to other publication	4	Manfredini 2016 & 2018, Rugh 1989, Shedden Mora 2013
	Not described	69	Abekura 2008, Ahlberg 2008, Baad-Hansen 2007, Baba 2005, Čadová 2014, Camara-Souza 2018, Carvalho Bortoletto 2016, Castro Mattia 2018, Castroflorio 2014 & 2015, Clark 1981, Clarke 1984 & 1984, Conti 2014, Deregibus 2014, Gallo 1997 & 1999, Haketa 2003, Hammoudi 2019, Harada 2006, Ikeda 1996, Iwasaki 2015, Jadidi 2008 & 2013, Jonsgar 2015, Karakoulaki 2015, Kardachi 1977, Khawaja 2015, Lee 2010, Maeda 2019, Mainieri 2012, Manfredini 2011, & 2019, Matsuda 2016, Matsumoto 2015, Minakuchi 2012, 2014 & 2016, Miyawaki 2003 & 2004, Mizumori 2013, Murakami 2014, Nagamatsu-Sakaguchi 2017, Needham 2013, Nitschke 2011, Ohlmann 2018 & 2020, Ono 2008, Palinkas 2019, Po 2013, Raphael 2013, Rugh 1981 & 1984, Sakagami 2010, Saueressig 2010, Schmitter 2015, Shimada 2019, Shochat 2007, Stock 1983, Stuginski-Barbosa 2015, Suganuma 2007, Takaoka 2017, Thymi 2019 & 2020, Wei 2017, Yachida 2012, Yamaguchi 2012 & 2018, Zhou 2016
A/D converter resolution	8 bit	7	Castroflorio 2014 & 2015, Deregibus 2014, Gallo 1997 & 1999, Stock 1983, Yamaguchi 2012
	10 bit	2	Po 2013, Raphael 2013
	12 bit	2	Maeda 2019, Yamaguchi 2018
	14 bit	1	Haketa 2003
	16 bit	1	Manfredini 2011
	Refers to other publication	7	Clarke 1984 & 1984, Kato 2018, Manfredini 2016, 2018 & 2019, Nitschke 2011
	Not described	58	Abekura 2008, Ahlberg 2008, Baad-Hansen 2007, Baba 2005, Čadová 2014, Camara-Souza 2018, Carvalho Bortoletto 2016, Castro Mattia 2018, Clark 1981, Conti 2014, Harada 2006, Hammoudi 2019, Ikeda 1996, Iwasaki 2015, Jadidi 2008 & 2013, Jonsgar 2015, Karakoulaki 2015, Kardachi 1977, Khawaja 2015, Lee 2010, Mainieri 2012, Matsuda 2016, Matsumoto 2015, Minakuchi 2012, 2014 & 2016, Miyawaki 2003 & 2004, Mizumori 2013, Mohamed 1997, Mude 2017, Murakami 2014, Nagamatsu-Sakaguchi 2017, Needham 2013, Ohlmann 2018 & 2020, Ono 2008, Palinkas 2019, Rugh 1981, 1984 & 1989, Saito-Murakami 2020, Sakagami 2010, Saueressig 2010, Schmitter 2015, Shedden Mora 2012 & 2013, Shimada 2019, Shochat 2007, Stuginski-Barbosa 2015, Suganuma 2007, Takaoka 2017, Thymi 2019 & 2020, Wei 2017, Yachida 2012, Zhou 2016
Sampling rate	10 Hz	1	Shedden Mora 2012
	16 Hz	1	Saito-Murakami 2020
	128 Hz	1	Murakami 2014

(Continues)

TABLE 4 (Continued)

	Outcome	*n*	First author & year
	200 Hz	2	Baba 2005, Haketa 2003
	800 Hz	3	Castroflorio 2014 & 2015, Deregibus 2014
	1000 Hz	9	Abekura 2008, Gallo 1997 & 1999, Harada 2006, Manfredini 2011, Matsuda 2016, Miyawaki 2003, Yamaguchi 2012 & 2018
	1001 Hz	1	Miyawaki 2004
	1002 Hz	1	Mizumori 2013
	1024 Hz	1	Lee 2010
	2000 Hz	7	Baad-Hansen 2007, Čadová 2014, Iwasaki 2015, Jadidi 2008, Khawaja 2015, Po 2013, Raphael 2013
	2001 Hz	1	Jadidi 2013
	2048 Hz	1	Matsumoto 2015
	4000 Hz	1	Stock 1983
	22 050 Hz	1	Mude 2017
	Refers to other publication	9	Clarke 1984 & 1984, Kato 2018, Manfredini 2016, 2018 & 2019, Nitschke 2011, Rugh 1989, Shedden Mora 2013
	Not described	38	Ahlberg 2008, Camara-Souza 2018, Carvalho Bortoletto 2016, Castro Mattia 2018, Clark 1981, Conti 2014, Hammoudi 2019, Ikeda 1996, Jonsgar 2015, Karakoulaki 2015, Kardachi 1977, Maeda 2019, Mainieri 2012, Minakuchi 2012, 2014 & 2016, Mohamed 1997, Nagamatsu-Sakaguchi 2017, Needham 2013, Ohlmann 2018 & 2020, Ono 2008, Palinkas 2019, Rugh 1981 & 1984, Sakagami 2010, Saueressig 2010, Schmitter 2015, Shimada 2019, Shochat 2007, Stuginski-Barbosa 2015, Suganuma 2007, Takaoka 2017, Thymi 2019 & 2020, Wei 2017, Yachida 2012, Zhou 2016

Abbreviation: *n*, number of studies.

raw EMG data reported the use of 10 different software programs, viz. the Bruxmeter software,[30,82-84,87] the Myomonitor software,[53] the Bruxism analysing software MTS50011,[96,97] Sound Engine software,[54] Chart 5,[91] SmartAnalyzer,[117] Biograph Infinity,[109] custom-made algorithms in the MatLab software,[19,57,59,60,70,108,111] LabVIEW[102,119] and Jaws.[32] Six studies reported the use of a custom software without further specification.[11,39,95,98,107,110]

Thirty (38%) studies[11,13,30,32,33,39,60,72-74,76-78,80,81,83,90,91,95-97,100-102,107,109,110,112,116,117] provided some description of which part of the signal was analysed, for example "the first and last 15 mins … of each night's recording were excluded from analysis". [32] There were three main ways of choosing a part of the signal for analysis, namely exclusion of a pre-defined period of recording time ($n = 10$),[30,32,78,96,97,100,107,109,112,116] device functioning for only a set amount of time ($n = 10$)[13,72-74,76,77,80,81,95,117] and utilisation of diaries with self-reported recording times ($n = 6$).[11,39,60,101,102,110] The four remaining studies used adjunctive measurements to help define which part of the signal should be analysed, viz. concomitant PSG,[33,83,90] and actigraphy.[91]

Signal rectification was performed in 17 (22%) studies[11,32,37,39,52,92,93,95,97,99,100,104,106,110,112,117] (Table 5). Other signal processing procedures were described in 23 studies 29%),[11,19,32,39,53,67,90-92,95-100,102,107-111,117] for example signal smoothing through root mean square conversion ($n = 10$)[19,32,53,67,95,98,100,102,108,117] (Table 5). Furthermore, additional filtering of the signal prior to scoring bruxism was described in five studies [19,54,90,100,101] (Table 5).

Twenty-five different thresholds were used for scoring of events on the EMG signal, the most common being a percentage of the MVC (Table 6). Forty-two studies (54%)[11,12,14,22,30-32,39,53,56,61,62,64,67-69,71,73,75-84,86-88,91,95-98,100,105,107,109,111] used a percentage of the MVC, ranging from 3%[32] to 50%,[11] with six of these studies using a 20% of 60% MVC threshold.[22,31,56,61,62,67] Six studies used a multiplication of the background EMG activity, viz. two times,[22,54,91] three times,[70] three standard deviations[92] and four standard deviations.[60] One study[90] used a combination of the above, that is >2 times baseline amplitude, and amongst those, bursts that exceeded 5%, 10% and 20% MVC. Fourteen studies[19,59,65,99,102-104,106,108,110,115,117-119] used other thresholds, that is 1,[106] 10,[102,119] 20,[103,104,118] 100 μV,[65] 20% of the highest occurring bursts,[99] percentages of 20 N bite-force thresholds,[19,59] the maximum amplitude of the signal of stimulated artefacts,[110] the average root mean square of muscle activity during three swallowing movements,[117] an A/D converter-related threshold[115] and a spectrogram-based frequency and power threshold.[108] Three studies[37,52,112] did not utilise a threshold for EMG scoring. Integrated EMG values per hour of sleep were used as outcome variables in one study[112] and recognition of pre-sampled EMG patterns in the other two[37,52] (Table 6).

Bruxism events were defined in various ways (see online appendix for a complete overview). Out of the 78 included studies, only nine (12%)[32,63,66,74,75,89,113,114,116] did not provide a description of how bruxism events were defined. Another five studies[14,61,68,85,100] referred to other publications for a description. Two studies did not utilise events, but integrated EMG values per hour of sleep,[112] and cumulative EMG activity divided by the duration of sleep[106] as measures of muscle activity. The remaining 62 (79%) studies provided descriptions of bruxism event definitions.

TABLE 5 Rectification, signal processing and additional filtering of EMG signal

	Outcome	*n*	First author & year
Rectification	yes	17	Abekura 2008, Baad-Hansen 2007, Baba 2005, Gallo 1997 & 1999, Haketa 2003, Jadidi 2008 & 2013, Kato 2018, Manfredini 2011, Miyawaki 2003 & 2004, Mizumori 2013, Mohamed 1997, Rugh 1989, Saito-Murakami 2020, Sakagami 2010
	Refers to other publication	1	Nitschke 2011
	Not described	60	Ahlberg 2008, Čadová 2014, Camara-Souza 2018, Carvalho Bortoletto 2016, Castro Mattia 2018, Castroflorio 2014 & 2015, Clark 1981, Clarke 1984 & 1984, Conti 2014, Deregibus 2014, Hammoudi 2019, Harada 2006, Ikeda 1996, Iwasaki 2015, Jonsgar 2015, Karakoulaki 2015, Kardachi 1977, Khawaja 2015, Lee 2010, Maeda 2019, Mainieri 2012, Manfredini 2016, 2018 & 2019, Matsuda 2016, Matsumoto 2015, Minakuchi 2012, 2014 & 2016, Mude 2017, Murakami 2014, Nagamatsu-Sakaguchi 2017, Needham 2013, Ohlmann 2018 & 2020, Ono 2008, Palinkas 2019, Po 2013, Raphael 2013, Rugh 1981 & 1984, Saueressig 2010, Schmitter 2015, Shedden Mora 2012 & 2013, Shimada 2019, Shochat 2007, Stock 1983, Stuginski-Barbosa 2015, Suganuma 2007, Takaoka 2017, Thymi 2019 & 2020, Wei 2017, Yachida 2012, Yamaguchi 2012 & 2018, Zhou 2016
Processing	Averaged signal	2	Gallo 1997, Harada 2006
	Averaged at 16 Hz	1	Matsumoto 2015
	Averaged with moving interval of 1 ms and window time of 19 ms	2	Miyawaki 2003 & 2004
	Converted to absolute value and smoothed with a width of 15 sampling points	1	Matsuda 2016
	Converted to absolute values and smoothed by a width of 101 points (.1 s)	1	Maeda 2019
	Root mean square	5	Baad-Hansen 2007, Ikeda 1996, Manfredini 2011, Raphael 2013, Saito-Murakami 2020
	Root mean square amplitude values calculated over 125-ms contiguous rectangular windows	1	Po 2013
	Root mean square conversion in 0.125-sec segments, and 0.0625-sec overlap of time segments	1	Lee 2010
	Root mean square conversion in 128-ms time-windows	1	Iwasaki 2015
	Root mean square conversion with integration time of 10 ms	1	Kato 2018
	Root mean square with average factor of 100 ms	1	Shedden Mora 2012
	Integrated signal, integration time 0.5 s	1	Gallo 1999
	Integrated signal, integration time was the entire duration of sleep	1	Mohamed 1997
	Integrated signal, but method not described	2	Čadová 2014, Mizumori 2013
	Performed, but method not described	2	Baba 2005, Haketa 2003
	Refers to other publication	3	Nitschke 2011, Rugh 1989, Shedden Mora 2013

(Continues)

TABLE 5 (Continued)

	Outcome	*n*	First author & year
	Not described	52	Abekura 2008, Ahlberg 2008, Camara-Souza 2018, Carvalho Bortoletto 2016, Castro Mattia 2018, Castroflorio 2014 & 2015, Clark 1981, Clarke 1984 & 1984, Conti 2014, Deregibus 2014, Hammoudi 2019, Jadidi 2008 & 2013, Jonsgar 2015, Karakoulaki 2015, Kardachi 1977, Khawaja 2015, Mainieri 2012, Manfredini 2016, 2018 & 2019, Minakuchi 2012, 2014 & 2016, Miyawaki 2003 & 2004, Mude 2017, Murakami 2014, Nagamatsu-Sakaguchi 2017, Needham 2013, Ohlmann 2018 & 2020, Ono 2008, Palinkas 2019, Rugh 1981 & 1984, Sakagami 2010, Saueressig 2010, Schmitter 2015, Shimada 2019, Shochat 2007, Stock 1983, Stuginski-Barbosa 2015, Suganuma 2007, Takaoka 2017, Thymi 2019 & 2020, Wei 2017, Yachida 2012, Yamaguchi 2012 & 2018, Zhou 2016
Additional filtering	200 Hz low-pass filter and 60 Hz notch filter	1	Mude 2017
	500 Hz low-pass filter and 60 Hz notch filter	1	Kato 2018
	20 Hz high pass filter	2	Maeda 2019, Matsuda 2016
	Low-level noise	1	Iwasaki 2015
	Refers to other publication	2	Nitschke 2011, Rugh 1989
	Not described	71	Abekura 2008, Ahlberg 2008, Baad-Hansen 2007, Baba 2005, Čadová 2014, Camara-Souza 2018, Carvalho Bortoletto 2016, Castro Mattia 2018, Castroflorio 2014 & 2015, Clark 1981, Clarke 1984 & 1984, Conti 2014, Deregibus 2014, Gallo 1997 & 1999, Haketa 2003, Hammoudi 2019, Harada 2006, Ikeda 1996, Jadidi 2008 & 2013, Jonsgar 2015, Karakoulaki 2015, Kardachi 1977, Khawaja 2015, Lee 2010, Mainieri 2012, Manfredini 2011, 2016, 2018 & 2019, Matsumoto 2015, Minakuchi 2012, 2014 & 2016, Miyawaki 2003 & 2004, Mizumori 2013, Mohaer 1997, Murakami 2014, Nagamatsu-Sakaguchi 2017, Needham 2013, Ohlmann 2018 & 2020, Ono 2008, Palinkas 2019, Po 2013, Raphael 2013, Rugh 1981 & 1984, Saito-Murakami 2020, Sakagami 2010, Saueressig 2010, Schmitter 2015, Shedden Mora 2012 & 2013, Shimada 2019, Shochat 2007, Stock 1983, Stuginski-Barbosa 2015, Suganuma 2007, Takaoka 2017, Thymi 2019 & 2020, Wei 2017, Yachida 2012, Yamaguchi 2012 & 2018, Zhou 2016

Abbreviation: *n*, number of studies.

Of those, five[12,39,54,94,99] used the SB/research criteria[29] to score EMG events. Another eight studies[56,57,64,84,96,97,102,119] used these criteria to score types of bruxism episodes, but based on a different threshold than the 20% MVC of the 1996 publication.[29] The remaining 49 (63%) studies used a variety of ways to define a bruxism event[11,13,19,22,30,31,33,37,52,53,59,60,62,65,67,69-73,76-83,86,87,90-93,95,98,101,103-105,107-112,115,117,118] (see Appendix S1). Definitions of events were based on criteria of EMG thresholds, duration of EMG activity above the threshold and interval between subsequent suprathreshold activity. With the exception of two studies,[37,52] all abovementioned studies with descriptions of bruxism event definitions ($n = 60$) included a threshold in their description of the event. Of these, 41 (53%) reported an additional duration criterion for the definition of an event,[11-13,19,30,31,33,39,53,54,56,57,59,60,64,65,67,69,70,73,78,79,90-99,102,105,107-111,115,118,119] and 22 reported a threshold, duration and interval criterion.[11,12,33,39,53,54,57,64,78,79,90,91,95-99,105,107,109-111] Eight studies used outcomes related to cardiac activity in the definition of a bruxism event.[30,82-84,86-88,98] Two studies[37,52] used a pattern recognition algorithm for the definition of events.

3.6 | Sleep bruxism outcomes

The term RMMA was used in the context of sleep bruxism outcome variables in nine studies.[33,57,83,84,91,96,97,108] Twenty-four studies (31%)[12,13,30,31,54,56,69,73-77,79-82,85,87,89,90,94,105] used cut-off criteria to define sleep bruxers. Of those, 13 studies used criteria to grade the severity of bruxism[13,71-77,79-81,87,89,90] (Table 7).

There were three main groups of sleep bruxism outcome variables: frequency, duration and intensity of masticatory muscle activity. Frequency variables were most commonly assessed, with 71 (91%) studies[11-14,22,30-33,37,52-54,56,57,60-89,92-99,101-105,107-111,113-119] reporting at least one frequency variable, followed by duration and intensity variables, which were reported in 28 (36%)[11,19,32,39,56,59,60,63,68,77,91-93,96,98,100-102,107-111,113,115,117-119] and 20 (26%)[32,56,59-61,63-65,91,98,101,106,107,109-113,115,117] studies, respectively. Forty-six (59%) studies[12-14,22,30,31,33,37,52-54,57,62,65-67,69-76,78-90,94,95,97,99,103-105,114,116] reported on frequency variables only, while three studies [19,39,100] reported on only duration measures, and two[106,112] solely on

TABLE 6 Thresholds for scoring EMG events

	Outcome	*n*	First author& year
% MVC	3%, 10% and 20% MVC	1	Baad-Hansen 2007
	5% MVC	1	Čadová 2014
	10% MVC	11	Camara-Souza 2018, Castroflorio 2014 & 2015, Deregibus 2014, Harada 2006, Manfredini 2011 & 2018, Matsumoto 2015, Miyawaki 2003 & 2004, Ohlmann 2018
	10% MVC (selected amongst 3%, 10% and 20% MVC)	1	Ikeda 1996
	10% and 20% MVC	3	Lee 2010, Matsuda 2016, Takaoka 2017
	20% MVC	7	Baba 2005, Jonsgar 2015, Kato 2018, Ono 2008, Saito-Murakami 2020, Thymi 2020, Yamaguchi 2018
	20% of 60% MVC	6	Conti 2014, Raphael 2013, Schmitter 2015, Stuginski-Barbosa 2015, Yachida 2012, Zhou 2016
	20% & 50% MVC	1	Haketa 2003
	30% MVC	11	Ahlberg 2008, Carvalho-Bortoletto 2016, Castro Mattia 2018, Karakouliaki 2015, Mainieri 2012, Minakuchi 2014, Murakami 2014, Nagamatsu-Sakaguchi 2017, Palinkas 2019, Saueressig 2010, Shochat 2007
Multiplication of background activity	> 2x baseline EMG activity during resting	1	Matsuda 2016
	2× baseline activity	1	Yamaguchi 2012
	2× baseline noise level during resting conditions of the mandible at the beginning of the recording	1	Mude 2017
	>3× amplitude of background noise	1	Thymi 2019
	>3× resting state standard deviations	1	Mizumori 2013
	4× standard deviation of background EMG activity while awake	1	Wei 2017
	>2× baseline amplitude, and amongst those 5%, 10% and 20% MVC	1	Maeda 2019
Other thresholds	1 μV	1	Mohamed 1997
	10 μV	2	Shedden Mora 2012 & 2013
	20 μV	3	Rugh 1981, 1984 & 1989
	100 μV	1	Clark 1981
	20% of highest occurring bursts	1	Gallo 1997
	5–9, 10–24, 25–49, 50–79 and ≥80% of 20 N force in each 128-ms time-window	1	Iwasaki 2015
	4 magnitude thresholds (10%, 25%, 50% and 20% of 20 N bite force) and 6 duration points (1, 2, 5, 10, 15 and 20 s)	1	Khawaja 2015
	Maximum amplitude of the signals of the stimulated artefacts	1	Gallo 1999
	Average RMS of muscle activity during three swallowing movements	1	Manfredini 2011
	Whenever the fourth least significant bit of the analogue-to-digital convertor was active, a bruxing episode was occurring	1	Stock 1983
	0.625 Hz peak frequency and 2% relative power	1	Po 2013
Not applicable	Signal recognition algorithm	3	Jadidi 2008 & 2013, Takaoka 2017
	Integrated EMG values of each analysed period	1	Abekura 2008

(Continues)

TABLE 6 (Continued)

	Outcome	*n*	First author& year
	Refers to other publication	3	Manfredini 2016, Nitschke 2011, Shimada 2019
	Not described	10	Clarke 1984 & 1984, Hammoudi 2019, Kardachi 1977, Minakuchi 2012 & 2016, Needham 2013, Ohlman 2020, Sakagami 2002, Suganuma 2007

Abbreviations: MVC, maximum voluntary contraction; *n*, number of studies; RMS, root mean square.

intensity. Twenty-two studies[11,32,56,59-61,63,64,68,77,91-93,96,98,101,102,107-111,113,115,117-119] reported on the combination of two or more variables of frequency, duration and intensity. An overview of reported outcomes is provided in Table 8.

4 | DISCUSSION

This scoping review provided a comprehensive overview of type 3 and 4 ambulatory EMG signal acquisition and analysis methods, and outcome measures used to date in sleep bruxism literature. Results showed a growing number of studies using ambulatory EMG devices for the assessment of sleep bruxism, especially in the past decade. This finding may reflect technological developments and an overall compliance with the recommendations given by an international group of experts to establish a definitive assessment of sleep bruxism through instrumental methods.[1,2]

4.1 | Recording hardware

Hardware was generally well described in all but two studies.[59,65] It is a quite straightforward recommendation that ambulatory EMG devices should have a simple design, with a minimum number of components and wires, for compliance and uncomplicated use in the home setting. For example, cable motion artefacts in the EMG signal can occur as a result of using wired electrodes.[43] Besides, wired and/or voluminous devices may be considered uncomfortable to wear during sleep, especially in the case of multiple night recordings. New, wireless type 4 devices that allow for whole night recordings have been introduced,[14,15] and their further development and validation against standardised PSG-AV assessments is recommended. Future developments may even include wireless type 2 and 3 recording devices,[121] allowing for concomitant assessments of, for example, electroencephalographic (EEG) and breathing. The masseter muscle was the site of preference in 58% of included studies.[11-14,30,32,33,39,54,65,72-88,90-92,94,98-111,117,118]

TABLE 7 Cut-off values and grading criteria for defining sleep bruxers

	Outcome	*n*	First author & year
Cut-off	>2 episodes/h	1	Camara-Souza 2018
	≥2 episodes/h	2	Murakami 2014, Schmitter 2015
	>4 episodes/h	3	Castroflorio 2015, Manfredini 2016, Mude 2017
	>25 events/h	1	Takaoka 2017
	SB/research criteria	2	Ono 2008, Suganuma 2007
	5.5 EMG-episode/h, 32.2 EMG-burst-all/h and 26.4 EMG-burst-5%/h	1	Maeda 2019
	18 EMG/h or higher in three consecutive nights and 19 EMG/h or higher in five consecutive nights	1	Stuginski-Barbosa 2015
Cut-off and grading	>2 episodes/h for moderate and >4 episodes/h for intense/severe sleep bruxism	2	Ohlman 2018 & 2020
	0 = <40 events; 1 = 40–74 events; 2 = 75–124 events; and 3 = ≥125 events (0–2: non-severe SB, score 3: severe SB)	1	Nagamatsu-Sakaguchi 2017
	0 = <40 events; 1 = 40–74 events; 2 = 75–124 events; and 3 = ≥125 events	2	Saueressig 2010
	0 = <30 events, 1 = 31–60 events, 2 = 61–100 events and 3 = ≥100 events	3	Carvalho Bortoletto 2016, Karakoulaki 205, Minakuchi 2012
	0 = <30 events, 1 = 31–60 events, 2 = 61–100 events and 3 = ≥100 events (0–1 normal controls, 2–3 severe SB)	1	Minakuchi 2014
	0 = no bruxism (≤39 episodes), 1 = mild bruxism (40–74 episodes), 2 = moderate bruxism (75–124 episodes) and 3 = severe bruxism (≥125 episodes)	3	Ahlberg 2008, Mainieri 2012, Palinkas 2019
	SB frequency score in four grades (0, 1, 2 and 3)	1	Minakuchi 2016

Abbreviations: EMG, electromyographic, h, hour, *n*, number of studies, SB, sleep bruxism.

TABLE 8 Types of sleep bruxism outcome variables based on frequency, duration and intensity of masticatory muscle activity

First author & year	Frequency	Duration	Intensity
Abekura 2008			Integrated EMG values/h (μV*s)
Ahlberg 2008	Score based on events/recording		
Baad-Hansen 2007	Events/h	EMG duration/h	EMG AUC/h
Baba 2005		Total duration of muscle activity/h, averaged across the 5-night study period	
Čadová 2014	Activity/h	Duration of activity (s)	Mean amplitude of contraction episode (%MVC)
			Max amplitude of contraction episode (%MVC)
			Integral under the signal curve of contraction episode (%MVC) (%MVC*s)
Camara-Souza 2018	Episodes/h		
Carvalho Bortoletto 2016	Score based on events/recording		
Castro Mattia 2018	Score based on events/recording		
Castroflorio 2014	Episodes/h		
	Episodes/ night		
Castroflorio 2015	Episodes/h		
	Episodes/ night		
Clark 1981	Activity/h		
Clarke 1984	Events/night		
Clarke 1984	Events/night	Duration of events	Intensity of bruxing as a factor of force and duration
		Total *n* of seconds bruxing/night	
Conti 2014	EMG events/h		
Deregibus 2014	Episodes/h		
	Episodes/ night		
Gallo 1997	Number of episodes		
Gallo 1999	Episodes/h	Duration of episodes	Mean amplitudes of episodes
	episodes/night	Intervals between episodes	Maximum amplitudes of episodes
			Integral (= muscle work, %MVC)
Haketa 2003	Events/h	Event duration/h	
	Events/night	Event duration/night	
		Event duration	
Hammoudi 2019	EMG grinds/hour	EMG burst duration	Intensity
	EMG grinds total *n*		
	EMG episodes/h		
	EMG episodes total *n*		
	EMG bursts/h		
	EMG bursts total *n*		
Harada 2006	Events/h	% event duration/night	total EMG activity
Ikeda 1996	Events/h	Mean EMG duration/ event	mean peak EMG level (%MVC)
Iwasaki 2015		Duty factor, that is the amount of time each muscle was activated at specific magnitudes during a given time, %	
Jadidi 2008	SRA events		

(Continues)

TABLE 8 (Continued)

First author & year	Frequency	Duration	Intensity
Jadidi 2013	SRA events		
Jonsgar 2015	Episodes/h		Mean burst duration
	Episodes total *n*		
	Grinds/h		
	Grinds total *n*		
	Bursts/h		
	Bursts total *n*		
Karakoulaki 2015	Score based on events/recording		
Kardachi 2017	*n* of bruxing units		
Kato 2018		Cumulative duration of each episode	
		Cumulative duration of episodes/h	
Khawaja 2015		Duty factor for duration of muscle activity threshold	Duty factor for magnitude of muscle activity threshold
Lee 2010	Events/h		
Maeda 2019	Episodes/h		
	Bursts/h		
Mainieri 2012	Score based on events/recording		
Manfredini 2011	Events/recording	Total MMA duration (s)/recording	
		Total MMA duration (s)/hour	Integrated EMG signal (μV x s)/recording
Manfredini 2016	Episodes/h		integrated EMG signal (μV x s)/hour
Manfredini 2018	Episodes/h		
	Phasic sleep-time masticatory muscle activity/h		
	Tonic sleep-time masticatory muscle activity/h		
	Mixed sleep-time masticatory muscle activity/h		
	Sleep-time masticatory muscle activity total number		
Manfredini 2019	Episodes/h		
	Phasic sMMA events/h		
	Tonic sMMA events/h		
	Mixed sMMA events/h		
	Total sMMA events/night		
Matsuda 2016		Coefficient of variation of interval duration	*n*-IEMG (integral values normalised by individual MVC)
		Coefficient of variation of burst duration	*n*-RMS (root mean square normalised by individual MVC)
		Coefficient of variation of cycle time	
		Interval duration	
		Burst duration	
Matsumoto 2015	Events/h	% event duration/night	total EMG activity
Minakuchi 2012	Score based on events/recording		
Minakuchi 2014	Score based on events/recording		
Minakuchi 2016	Score based on events/recording		

(Continues)

TABLE 8 (Continued)

First author & year	Frequency	Duration	Intensity
Miyawaki 2003	Episodes/h	Episode duration	
Miyawaki 2004	RMMA episodes/h		
	Short-burst episode/h		
	Clenching episode/h		
	Other EMG episodes/h		
Mizumori 2013	Events/h	Event duration	
	Events/night		
	Bursts/event		
Mohamed 1997			Cumulative EMG activity (μV.s) divided by the duration of sleep (min)
Mude 2017	Phasic episodes/h		
	Tonic episodes/h		
	Mixed episodes/h		
Murakami 2014	Events/h		
	Events/night		
Nagamatsu-Sakaguchi 2017	Score based on events/recording		
Needham 2013	Number of clenching/grinding episodes/week		
Nitschke 2011	Activity periods/h	Activity periods duration	Mean amplitudes (%MVC)
	Activity periods/night		Max amplitudes (%MVC)
			Time integral (%MVC)
Ohlmann 2018	Episodes/h		
Ohlmann 2020	Episodes/h		
Ono 2008	Episodes/h		
	Episodes/night		
	Burst/episode		
	Bruxism/h		
Palinkas 2019	Score based on events/recording		
Po 2013	RMMA episode frequency (Hz)	Pooled RMMA episodes duration	
	episodes/ night		
Raphael 2013	Events/ min		
Rugh 1981	Mean number of events	Mean duration of events	
Rugh 1984	EMG units		
Rugh 1989	μV/sec		
Saito-Murakami 2020	Events/recording		
Sakagami 2002	episodes/h	Total bruxism time/h	
		Bruxism lasting time	
Saueressig 2010	Score based on events/ recording		
Schmitter 2015	Episodes/h	Burst duration	Intensity
	Bursts/h		
Shedden Mora 2012	Rhythmic NMMA episodes/h	rhythmic NMMA episode duration/h	
	EMG bursts/h	EMG bursts duration/h	
	Burst/episode		
Shedden Mora 2013	Bursts/h	Durations of bursts/h	

(Continues)

TABLE 8 (Continued)

First author & year	Frequency	Duration	Intensity
Shimada 2019	Events/h		
Shochat 2007	Events/recording		
Stock 1983	*n* episodes	Duration (not further specified)	Severity (not further specified)
Stuginski-Barbosa 2015	Events/h		
	Total number of events		
	Coefficient of variation from the multiple night recordings (CV =SD/mean)		
Suganuma 2007	Episodes/h		
	Episodes/night		
	Burst/episode		
	Bruxism/h		
Takaoka 2017	Events/h		
Thymi 2019	Events/recording		
	Events/h		
	Coefficient of variation (CV = SD/mean)		
Thymi 2020	Episodes/h	Bruxism time index (% time bruxing/total sleep time)	
Wei 2017	Clench episodes/h	Mean clench duration	Mean clench bite-force
	Clench episodes number	Clench-related temporalis duty factor (sum of clench episode durations / total recording time)	
Yachida 2012	Events/h		
	Number of events		
	Night-to-night variability (CV = SD/mean)		
Yamaguchi 2012	Episodes/h		
	Episodes/night		
Yamaguchi 2018	Bursts/h		
Zhou 2016	Events/h		Intensity of the EMG (area under EMG curve)

Abbreviations: AUC, area under the curve; CV, coefficient of variation; EMG, electromyographic; h, hour; MVC, maximum voluntary contraction; *n*, number; NMMA, nocturnal masticatory muscle activity; RMMA, rhythmic masticatory muscle activity; SD, standard deviation; sMMA, surface masticatory muscle activity; SRA, signal recognition analysis.

The choice of recording site, that is temporalis or masseter muscle, can be guided by practical aspects, such as the presence of facial hair. It can be argued that both sites can provide valid data in terms of masticatory muscle activity during sleep, as long as appropriate impedance levels are assured[122] and recordings undergo thorough quality control for signal-to-noise ratios.

4.2 | Recording logistics

Sleep bruxism has a time-variant nature,[41,42] which obviously requires multiple recordings to capture this particular feature. Multiple night recordings were performed in the majority of included studies,[11,13,15,19,22,31,32,37,39,52,53,57,59-67,69-72,74,75,77,84,86,87,89,93,95,98,101-104,106,107,109-114,116,118,119] showing that ambulatory EMG devices are well suited for such assessments.

Proper instructions to participants for handling an EMG device and/or its components are important to enable its flawless functioning and were given in 57% of included studies.[11-14,19,22,30,31,37,39,52,53,56,59,60,63-66,69-71,73-76,80,82,84,87,92-95,102,105,107,109,110,114,117,119] Correct placement of the device is crucial in order to obtain good recordings and prevention of artefacts due to, for example, improper skin cleaning that could result in high skin-electrode impedance.[43] Therefore, it is recommended that the use of the device is trained with participants, either face-to-face or through tele-medicine, and written and/or recorded instructions are provided for reference at home.

Set-up procedures, that is performance of grimaces, MVCs, etc., for reference purposes were applicable for 47%

of included studies.[11,14,22,30,31,37,39,52-54,56,61,62,67-69,73,77,78,80-84,90,91,95,96,98,100,101,107-111,117] Such procedures may be source of variability and can complicate study protocols.[68] In line with the recommendation of the use of simple devices, it can be suggested that only simple and sufficiently standardised set-up procedures should be preferred, if not avoided altogether.

Finally, on the topic of recording logistics, it is notable that 58% of the studies[12,13,19,30,31,33,60,61,65-67,71,72,74,75,77-91,94,96-98,100,103-106,111-113,115,116,118] did not report on how failures were dealt with. Failures in ambulatory EMG recordings can be divided in two categories. The first is quite straightforward, namely the failure of performance of a part or the entire recording due to detachment or improper placement of the electrode.[22,62,68,73] The second is the presence of artefacts in the EMG signal as a result of high noise levels.[43] Failures can be prevented by adequate device handling and tackled with pre-set quality criteria, which should include a minimal number of recording nights, and a minimal number of recording hours with acceptable signal-to-noise ratio. Ideally, ambulatory EMG recorders should have built-in features for automatic quality checks of proper placement and connection of the electrode, good functioning of the device, impedance measurements and signal-to-noise ratio. Smartphone technologies can be developed to facilitate these functions.[15] It is recommended that future studies employ and report quality criteria based on which recordings are considered failures, in line with similar recommendations given by the American Academy of Sleep Medicine (AASM) for the performance of Out of Centre Sleep Testing (OCST).[123] The OCST standards[123] are an excellent example of comprehensive quality reporting of ambulatory sleep recordings. Similar standards for ambulatory EMG recordings of masticatory muscle activity would be a valuable development in the field.

4.3 | Signal acquisition

Adequate reporting on signal acquisition features in EMG studies is recommended by the International Society of Electrophysiology and Kinesiology (ISEK).[45] It allows the reader to identify whether the signal was acquired in a correct way, and facilitates comparison between different studies. Results of the present study show that basic elements of signal acquisition, that is amplifications factors, impedance, bandpass settings, notch filtering, A/D converter resolution and sampling rates, were largely underreported. Underreporting of methodology in EMG studies of masticatory muscles has been described previously. In their systematic review of EMG studies published in 2004, Armijo-Olivo et al. found that less than 50% of the items proposed by ISEK were reported in approximately 91% of assessed studies.[46] As the authors of this review state, maximum word counts and editorial limitations may contribute to underreporting, and online appendices may help overcome this issue.[46] Moreover, it may be hypothesised that authors' (lack of) knowledge of the recording processes may affect the way these are reported in a publication.

In addition, quite some variability was encountered amongst studies for certain signal acquisition variables. It is beyond the scope of this review to recommend the ideal features of signal acquisition from the masticatory muscles. The reader is referred to other publications, for example.[43-45,122,124] Here, some brief comments will be made. Surface EMG measures very small amplitudes, that is microvolt to millivolt, and appropriate amplification is needed, in order to allow proper processing and recording of the signal.[43,122] Furthermore, external interfering signals with a so-called 'common mode', that is equal in phase and amplitude, need to be eliminated during the amplification process in order to reduce noise in the EMG signal.[122,125] Amplification factors of at least 500[122] and 1000,[124] with a high common mode rejection ratio, that is >95 dB,[44,122] have been recommended. In the present review, only three studies reported amplification factors smaller than the recommended 500.[14,90,115] Furthermore, bandpass settings starting from 5–10 Hz (high pass)[45] to 400–500 Hz (low pass)[45,122] have been recommended for surface EMG. In the present review, bandpass settings ranging from 5–500 Hz[90] to 251–610 Hz[61] were encountered. In a number of studies, the high pass filter may have been too high, with a possible consequence of amplitude loss and introduction of artefacts.[43,126] Moreover, as per the Nyquist theorem, the signal sampling rate should be at least twice the highest frequency cut-off of the bandpass filter,[43,45] and even higher sampling rates are preferred. Consequently, for surface EMG, sampling rates of at least 1000 Hz are advised,[45,125] though up to 5000 Hz sampling has also been recommended.[43] Sampling rates in studies included in the present review were mainly around 1000[14,33,53,91,92,96,97,99,107,110,112,117] and 2000 Hz,[19,32,37,52,59,67,108,109,111] that is within acceptable limits.

4.4 | Signal analysis

There was an equal number of studies in which EMG devices produced raw EMG signal vs devices in which activity was automatically scored (38%[19,30,33,39,53,54,57,59,60,68,70,83,84,90-92,96-98,100-102,107-109,117-119] and 38%,[13,22,31,56,61,62,64-67,69,71-81,88,93,103,104,111,113-116] respectively). Providing scored output has the obvious benefit of simplifying the data collection process. Moreover, it can help reduce investigator-related measurement errors.[98] However, this requires consensus on the topic of the ideal sleep bruxism scoring method, which, as will be discussed further on, is not yet the case. Furthermore, one should be mindful of the fact that skipping evaluation of the raw EMG signal poses the risk of scoring low quality signal, in terms of signal-to-noise ratio and presence of other artefacts.

Importantly, ambulatory type 4 EMG recordings are well known for their inability to correctly identify the actual amount of sleeping time compared to PSG assessments.[3,4] Subsequently, investigators are forced to implement alternative methods for defining sleep time in a recording. The current review showed that only a minority of studies, viz. 38%,[11,13,30,32,33,39,60,72-74,76-78,80,81,83,90,91,95-97,100-102,107,109,110,112,116,117] provided some description of which part of the signal was analysed as sleep time. Different methods were used, the most important being excluding a pre-defined amount of time from the start and/or end of the recording, [30,32,78,96,97,100,107,109,112,116] device functioning

for only a set amount of time,[13,72-74,76,77,80,81,95,117] and subjective sleep diaries.[11,39,60,101,102,110] Having different criteria for choosing the length of the recording to be analysed can be an important source of variation amongst different studies. Alongside, abovementioned methods have their limitations, such as excluding actual sleep time for the first two methods, and biased subjective reports and/or forgetting to fill out diaries for the third. Future investigations may consider the use of evolving technologies of wrist-worn personal health monitoring devices[127,128] to define sleep time and overcome these issues. Alternatively, it is advised that studies at least include a description of analysis time in their publications. Other interesting developments are found in the field of portable PSG devices, that is self-applicable electrode sets that allow for electroencephalographic (EEG) recordings, based on which sleep-wake states can be discriminated more accurately.[121,129] As the authors of these publications suggest, further development and simplifications of these devices and electrodes may prove extremely useful for the field of at-home assessments of sleep bruxism, and possible also other sleep disorders.[121,129]

The variables rectification, signal processing and additional filtering of the EMG signal were largely left undescribed in the included studies. As discussed for the topic of signal acquisition variables, it is recommended that publications include descriptions of these procedures.[45,46]

Twenty-five different thresholds were used for scoring the sleep bruxism events, with a percentage of the MVC being the most common. The lack of unanimous thresholds to score sleep bruxism events is a topic that has been discussed for over two decades in the field.[10,98] The %MVC method started to be used for scoring sleep bruxism events in PSG studies in the mid-80 s by Phillips et al.[130] These authors, as well as Okeson et al. in 1990,[131] used a 40% MVC threshold to score bruxism events, based on the belief that a smaller threshold would be confused with swallowing.[130,131] A 20% MVC criterion was used in the widely implemented scoring criteria proposed in 1996 by Lavigne et al.[29] As the authors of this PSG study state, this threshold 'was the most frequently associated, when controlled with audio-video signals, to the beginning of a bruxism episode'.[29] However, in the same year, Ikeda et al. argued that, based on the results of their EMG-ECG study on the development of criteria to score bruxism events, a 10% MVC threshold should be utilised, with 20% and 40% MVC thresholds being too high.[98] Despite these findings, thresholds of both 10% MVC[34] and 20% MVC[42] were adopted in future publications, and, as seen from the results of the present study, also other values have been used over the years in EMG studies, for example 30% MVC,[71] and 20% of 60% MVC.[62] The use of the multiplication of baseline EMG activity was introduced by the AASM in 2007,[132] with the recommendation to use a threshold of at least two times the baseline amplitude of background EMG of chin EMG activity. This recommendation was kept in subsequent versions of the AASM scoring manual.[133] Raphael et al. used twice the amplitude of relaxed EMG levels while awake in their PSG study, published in 2012,[134] and further work.[135] A few other authors used multiplications of baseline activity in their studies in the following years, for example Mizumori et al.[92] and Maluly et al.[136]

Thus, so far, it can be concluded that %MVC thresholds are widely implemented in sleep bruxism research, and that little consensus exists amongst research groups as for the ideal MVC threshold for scoring sleep bruxism events. Furthermore, multiplications of baseline EMG activity have been recommended and implemented to a lesser extent than the %MVC threshold, perhaps due to the fact that this approach is relatively novel as compared to the %MVC method.

Ideally, a single threshold should exist to be used amongst research groups, and future studies are encouraged to focus on establishing this. Here, several issues that affect the choice of such a threshold will be discussed. An ideal threshold should be valid, that is adequately distinguish events from non-events. In PSG-AV recordings, this means distinguishing MMAs related to sleep bruxism, from other muscle activities, that is OFAs and OMAs.[3,7,8] Limited availability of PSG facilities and growing use of ambulatory EMG recorders has led to a thorough revision of concepts regarding how masticatory muscle activity should be assessed within the construct of bruxism.[9] Registrations performed by ambulatory EMG recorders in general assess only MMA, with some exceptions with simultaneous audio recordings (eg[96]), and assessment of cardiac activity (eg[84]). Therefore, they do not allow for relating MMAs to grinding sounds, microarousals or other activities such as swallowing, yawning and/or other body movements, as is the case for PSG-AV recordings. Subsequently, strictly taken, OFAs and OMAs cannot yet be scored based on ambulatory EMG recordings. Even so, ambulatory EMG recorders allow for recording the full spectrum of masticatory muscle activity during sleep, and, as argued in the Background section, are very potent alternatives for PSG-AV for large-scale studies and/or multiple night recordings. Given the above, it seems reasonable to suggest the use of a different scoring strategy for PSG- and EMG-derived recordings. This follows the line of reasoning by Manfredini et al.[9] who suggested that a clear distinction should be made between sleep bruxism scored on PSG-AV recordings, that is PSG/SB, and masticatory muscle activity scored on ambulatory EMG recordings, that is EMG/MMA. As pointed out in the same publication,[9] the definition of a sleep bruxism event may need to shift from the concept of events being related to microarousals as an exclusive association,[137] to events being a part of a spectrum of MMA in broader sense, that is unrelated to other sleep variables, such as microarousals.[9] Instead, EMG/MMA events, and the thresholds used to score them, may need to be defined based on which clinical outcome is investigated, for example tooth wear and pain[9,10] This topic will be elaborated in the next section of this discussion.

Alongside with the issue of threshold validity, one should be mindful of factors which may influence its reliable acquisition. An overview of such factors will be given here, in order to assist the ongoing discussion on the choice of an ideal threshold. Using the MVC as a reference value to normalise EMG data is a common and practical way in EMG analysis to overcome the issue of variability in amplitudes between and within individuals.[122,125,138] It allows for the expression of the magnitudes of EMG tasks as percentages of a reference value, instead of μV or mV.[139] In the dental field, an

MVC is relatively easy to perform, for example by having the participant clench in the maximal intercuspal occlusion, or on materials such as rubber tubing, wax or cotton rolls.[140] Differences in acquisition methods may affect the magnitude of the MVC. Mapelli et al. showed that clenching on an arch-shaped wax pad of 2 mm thickness produces MVCs of significantly higher amplitude and with better test–retest repeatability than clenching on cotton rolls of 10 mm thickness.[140] Moreover, the lack of appropriate training and instruction of participants in performing maximal contractions have an important influence on the MVC[45,138] and will most likely lead to submaximal contractions,[139] and consequently to an overestimation of sleep bruxism events. Encouragement of study participants and visual feedback of provoked EMG activity can lead to achieving actual MVCs in healthy, pain-free individuals.[139] In the home setting, such encouragement and feedback are not readily available, and investigators have little control on whether MVCs are performed correctly. In fact, it has been shown that MVCs can altogether be forgotten to be performed by a substantial number of study participants, resulting in not scorable recordings and subsequent data loss.[68] New technologies, such as smartphone apps and online platforms, can prove extremely useful in this context,[15] through providing reminders and instruction videos for performing the MVCs, and even real-time feedback regarding the EMG/MVC level.[141]

Pain is another important factor that can influence the acquisition of an MVC. It is recommended that the MVC normalisation method is used in healthy individuals without pain and/or injuries, since these conditions will most likely lead to the performance of submaximal contractions.[122,139] This is unfortunate for sleep bruxism studies, in which individuals with pain in the masticatory system are often investigated. It has been shown that the force, measured in N, which is exerted during maximal contraction on force transducers, is decreased in individuals with pain in the masticatory system, compared to pain-free controls.[142,143] In addition, Manfredini et al. found that in individuals with myofascial pain the level of EMG activity of masticatory muscles was significantly lower compared to pain-free controls, during maximum clenching on cotton rolls.[144] On the other hand, Lobbezoo et al. found that even though the EMG amplitude of a MVC in maximal intercuspal occlusion and on biting on a bilateral bite-fork was lower in individuals with pain in the masticatory muscles compared to pain-free controls, this difference was not statistically significant.[145] The authors do mention, however, that this lack of statistical significance may be related to the small sample size.[145] Furthermore, Giannakopoulos et al. found an increase in maximum biting EMG activity in intercuspation after pain-reduction following treatment of non-dysfunctional myofascial TMD pain.[146] Thus, it remains plausible that the MVC in masticatory muscles is affected by the presence of pain and that subsequently, a sleep bruxism scoring threshold that relies on MVC is not ideal in samples with pain. More research on the exact differences between the overall MVC levels of patients with pain as compared to pain-free individuals might allow the use of an 'adjusted' MVC threshold, that is an MVC threshold that is adjusted depending on the presence of pain. As another alternative, the use of submaximal EMG levels can be considered[122] and has indeed been used in a number of studies included in this review.[22,31,56,61,62,67] However, this method too can be sensitive for errors and will require careful training of study participants, as well as close monitoring of correct performance through, for example, real-time feedback practices, as discussed above.

On the other hand, the multiplication of the amplitude of background EMG has the advantage of being less demanding for the participant, hereby overcoming the issues of submaximal 'maximal' contractions, forgetting to perform MVCs, and influences of different MVC acquisition methods. In this sense, it may be an interesting threshold to be used in cases where cooperation is challenging, such as paediatric populations and individuals with developmental disabilities. This method has been recommended by the AASM[132,133] for scoring sleep bruxism activity in PSG-AV recordings and seems a promising alternative for the %MVC methods. However, EMG activity of masticatory muscles is found to be higher during wakefulness, compared to sleep.[147] What is more, the levels of background activity have been associated with the presence of chronic pain both during sleep,[18] as well as wakefulness.[148] More specifically, Raphael et al.[18] showed in a PSG study a small, but statistically significant elevation of background EMG activity of masticatory muscles during sleep in patients with myofascial TMD pain, compared to controls. Moreover, the AASM guidelines[132,133] recommend a period of at least 3 s of stable background EMG before a sleep bruxism event can be scored. However, variation of background EMG activity over the course of a night may occur, as a result of sweat, secretions of sebaceous glands and changes in conductance, with possible influences on scoring of events. As for muscle activity during wakefulness, Bodéré et al.[148] found increased masticatory muscle EMG activity at rest for individuals with different types of oro-facial pain, that is myofascial and neuropathic, compared to controls. On the other hand, other studies have not found differences in EMG activity of masticatory muscles at rest in individuals with TMD pain[149] or headache,[150] compared to pain-free controls, nor between the EMG activity of masticatory muscles on the painful and non-painful sites in patients with unilateral myofascial pain.[151] Thus, it is possible that the presence of pain is positively associated with differences in background EMG activity in sleep and awake states, and if so, using it as a threshold to score sleep bruxism events will lead to underdiagnosing sleep bruxism in individuals with pain.

Other thresholds, such as specific EMG amplitudes (μV),[65,102-104,106,118,119] percentages of the highest occurring bursts,[99] or bite-force thresholds,[19,59] and the mean amplitude of swallowing movements[117] were encountered in included studies. EMG amplitude data are known to be influenced by a number of factors and can greatly vary between and within individuals[122]; therefore, thresholds based on absolute amplitude values, such as 10 μV, are discouraged. The use of swallowing movements,[117] percentages of highest occurring bursts,[99] as well as percentages of bite-force with corresponding EMG values[19,59] deserve further research. The latter may be interesting specifically in the field of investigating clinical outcomes such as tooth wear and other dental complications, in which the degree of force applied to the dental tissues and/or materials is relevant for the occurrence of complications.

Taken together, based on the above discussion on factors with impact on MVC and background EMG activity values, it can be suggested that the MVC method is suitable for normalising EMG data, and as such a good threshold candidate. On the other hand, it has the drawbacks that its acquisition is influenced by participant cooperation and the presence of pain. A multiplication of background EMG activity is less depending on participant compliance, but may also be influenced by wake–sleep state, as well as the presence of pain. Alternatives include, amongst others, percentages of highest occurring bursts, swallowing, etc. Clearly, more research is needed before broad consensus can be reached on this topic.

4.5 | Sleep bruxism outcomes

The results of this review showed that sleep bruxism outcome variables fell into three categories, viz. representing frequency, duration and intensity of MMA, or a combination of two or more categories. Current visions on sleep bruxism assessment support that different sleep bruxism variables, representing different expressions of muscle work, could be related to different clinical outcomes.[9,10] As a speculative example, it may be plausible that when investigating pain as a health outcome, frequency and duration of MMA are important predictor variables, whereas duration and intensity could be more relevant in a study on tooth wear or failures of dental restorations. In the latter case, the duration and type of tooth contact would also be interesting predictor variables. A pivotal first step for further development of this concept is the choice of an appropriate threshold for scoring activity on the EMG signal. Next steps could include the classification of EMG devices according to the type of MMA outcomes they are able to asses, in a way similar to the classification of obstructive sleep apnoea devices for out-of-centre testing.[152]

Furthermore, it was found that the RMMA term was used as a sleep bruxism outcome variable in nine studies.[33,57,83,84,91,96,97,108] As discussed above, defining only RMMA's based on ambulatory EMG devices while ignoring other forms of MMA may not be a representative approach. Instead, clearly defined criteria for scoring EMG/MMA may be more relevant for future studies on the association between sleep bruxism (and sleep MMA in the broader sense) and health outcomes.

Taken together, and in line with previous publications,[9,10] it is emphasised that in the field of research with ambulatory EMG recordings a) the focus may need to shift from the concept of scoring sleep bruxism, to that of scoring the whole spectrum of masticatory muscle activity, and b) masticatory muscle activity variables should carefully be selected, based on the assessed health outcome.

4.6 | Strengths and limitations

This scoping review has several strengths, the most important of which is its relevance for revealing the evolution of sleep bruxism research. It is the first review that provided a comprehensive and structured overview of signal acquisition and analysis methods used in sleep bruxism studies utilising ambulatory EMG recorders in the past five decades. As such, its results can form a reference point for the rapidly evolving research field of sleep bruxism and can assist researchers, and the industry, in the design and conduct of high-quality future studies, and in the further development of ambulatory EMG recorders. Furthermore, the results of the study also highlighted the diversity in sleep bruxism outcomes, the importance of scoring the whole spectrum of masticatory muscle activity during sleep and the subsequent need for working towards clearly defined scoring criteria.

Limitations need to be acknowledged as well. The most important is that relevant articles that did assess masticatory muscle activity during sleep but did not use the term 'bruxism' may possibly have been missed by our search strategy. This is a limitation that needs to be accepted, since the starting point and main aim of the review was to address the topic of sleep bruxism. The issue of assessing sleep bruxism activity vs. the whole spectrum of masticatory muscle activity was extensively addressed in the discussion of this review, arguing that indeed, in the field of ambulatory EMG recordings, it may be more fruitful and clinically relevant to shift the focus towards a standardised assessment of the whole spectrum of MMA.

5 | CONCLUSION

The main conclusions of this scoping review per topic are as follows:

1. Recording hardware: Recording hardware was generally well described, and it is recommended that future studies continue to do so. Further development of simple, and if possible, wireless devices is encouraged.
2. Recording logistics: Ambulatory EMG devices are well suited for multiple night recordings. Reports of participant instructions in device handling and dealing with failed recordings were often lacking. Proper reporting hereof is recommended.
3. Signal acquisition: Basic elements of signal acquisition, for example amplifications factors, impedance and bandpass settings, were generally underreported. It is recommended that studies follow established surface EMG signal acquisition guidelines, and adequately report on those, or refer to a paper describing these.
4. Signal analysis: The part of the signal that was analysed, and rectification, signal processing and additional filtering of the signal were often underreported. Here too, adequate reporting it is highly recommended. Extensive variability was found for thresholds use to define sleep bruxism events, and further research on the topic that takes into consideration the limitations of each type of threshold is highly recommended.
5. Sleep bruxism outcomes: Outcomes represented frequency, duration and intensity of masticatory muscle activity, or a combination of two or more categories. Future studies need to take into consideration that variables scored on a signal acquired by an

ambulatory EMG device are different entities than those scored by PSG recordings. Finally, it is recommended that the focus may need to shift from the concept of scoring sleep bruxism events to that of scoring the whole spectrum of MMA.

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CONFLICT OF INTEREST

Dr. Aarab reports grants from Sunstar Suisse SA and TKI Health Holland related to this work, and grants from SomnoMed-Goedegebuure and Vivisol BV outside of this work. Dr. Ahlberg has nothing to disclose. Dr. Baba has nothing to disclose. Dr. Carra has nothing to disclose. Dr. De Laat has nothing to disclose. Dr. Gallo has nothing to disclose. Dr. Lavigne reports free access to recording devices without any financial link. Dr. Lobbezoo reports grants from Sunstar Suisse SA, SomnoMed-Goedegebuure, Airway Management and Vivisol BV outside of this work. Dr. Manfredini has nothing to disclose. Dr. Svensson reports personal fees from Sunstar Suisse SA outside of this work. Dr. Thymi reports grants from Sunstar Suisse SA and TKI Health Holland related to this work.

AUTHOR CONTRIBUTIONS

All co-authors actively took part in the conceptualisation and preparation of this manuscript. MT performed the analysis of data and drafted a first version of the manuscript. FL, GA, JA, KB, MCC, LG, AL, DM, GL and PS revised the manuscript.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that were used for the synthesis of results in this manuscript are available as an online appendix.

ORCID

Magdalini Thymi https://orcid.org/0000-0002-8544-6495
Frank Lobbezoo https://orcid.org/0000-0001-9877-7640
Ghizlane Aarab https://orcid.org/0000-0002-6677-7897
Jari Ahlberg https://orcid.org/0000-0002-6052-0441
Kazuyoshi Baba https://orcid.org/0000-0001-8025-2168
Antoon De Laat https://orcid.org/0000-0003-3558-1418
Daniele Manfredini https://orcid.org/0000-0002-4352-3085

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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