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SOMAS – an open-source software for the analysis of muscle activity during sleep

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ABSTRACT

Study objectives: While several algorithms exist for analyzing muscle activity during sleep, none provides information on both muscle tone and movements as open-source software. We aimed to overcome this limitation by developing SOMAS (Sleep Open-source Muscle activity Analysis System).
Methods: SOMAS processes European Data Format+ (EDF+) files with wake-sleep state and candidate leg movement annotations without online data sharing, quantifies muscle tone using the atonia index and the distribution of normalized electromyography values (DNE), and calculates leg movement indices based on the 2016 World Association of Sleep Medicine criteria. To demonstrate that SOMAS achieves its intended purpose, we analyzed recordings from eight patients with isolated REM sleep behavior disorder (iRBD), five with restless legs syndrome (RLS), seven with sleep breathing disorders, and five controls. SOMAS-derived atonia index and leg movement indices were compared with those from Hypnolab, a non-open access software. Additionally, SOMAS-derived indices were used to differentiate patients with iRBD or with RLS from other patients and/or controls.
Results: SOMAS-derived atonia index and leg movement indices strongly correlated with Hypnolab results (Spearman coefficients >0.97) with minimal bias. The DNE and atonia index in REM sleep effectively differentiated patients with iRBD from other patients and controls (AUC 0.89–1.00). The periodic leg movement and periodicity indices differentiated patients with RLS from controls (AUC 0.71–0.75).
Conclusions: SOMAS reliably quantifies muscle tone and movements during sleep from EDF+ files using open-source algorithms, with the potential of enhancing reproducibility and collaboration in research on sleep-related movement disorders.

1. Introduction

The evaluation of muscle activity during sleep is an important topic for clinical sleep research, but the number of automatic tools is limited. For example, demonstration of rapid eye movement (REM) sleep without atonia (RWA) is an essential component of REM sleep behavior disorder (RBD). As manual quantification of RWA is a time-consuming task and prone to inter-rater variability [1,2], implementation of reliable automatic methods is highly needed. Although several RWA quantification algorithms have been proposed [3], only few of them are available as standalone applications with graphical user interfaces. Table 1 summarizes them, their characteristics and limitations.

Among the automatic RWA quantification algorithms that have been proposed, the REM atonia index (RAI) [5,6] has shown robust performance for automatic identification of patients with RBD [10–12], but an open-source and open-access software for its implementation is still not available. An advantage of this algorithm is that it can be easily applied also to non-REM sleep, thus extending the calculation of the atonia index across all sleep stages, which has been shown to be useful in several contexts [13,14].

Similarly to the atonia index, the distribution of normalized electromyographic (EMG) values (DNE) [15] is an automated method that allows estimation of muscular activity across different sleep stages. DNE applications showed its usefulness in RBD [15], narcolepsy [16], and neurodegeneration [17] research. Also for DNE, currently no open-source and open-access software is available.

The evaluation of periodicity of leg movements (LM) during sleep and wakefulness also has diagnostic utility. In 2016, standards to

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Table 1
Overview of currently available software for RWA quantification.
EDF: European Data Format; PSG: polysomnography; REM: rapid eye movement; RWA: REM sleep without atonia; SINBAR: Sleep Innsbruck Barcelona.

Software name	Characteristics	Limitations
Hypnolab [4]	Quantifies RWA with REM atonia index [5,6].	Not open-source. Not open-access. Input data in EDF format, requiring separate software-specific annotation file.
RBDtector [7]	Open-source and open-access software quantifying RWA according to SINBAR scoring [8].	Input data in EDF format, requiring separate software-specific annotation file.
SINBAR [9]	Tool integrated in a commercial PSG software that quantifies RWA according to SINBAR scoring [8].	Not open-source. Not open access. Input data in EDF format, requiring separate software-specific annotation file.

Table 2
Overview of currently available software for leg movement periodicity calculation
EDF: European Data Format; PSG: polysomnography; REM: rapid eye movement; RWA: REM sleep without atonia; SINBAR: Sleep Innsbruck Barcelona.

Software name	Limitations
Hypnolab [4]	Not open-source. Not open-access. Input data in EDF format, requiring separate software-specific annotation file.
PLMScoRe [21]	Input data consist only of annotations in a specific PSG-generated software.
Polyman [22]	Not open-source. Not open access. Input data in EDF format, requiring separate software-specific annotation file.

quantify LM periodicity were proposed by the World Association of Sleep Medicine (WASM) [18]. These standards defined not only periodic LM during sleep (PLMS), but also non-periodic (short-interval and isolated) LM during sleep [18], which are important in several contexts [19,20]. Table 2 lists the currently available periodicity calculator software, which are available as standalone applications with graphical user interfaces. Their limitations are highlighted in the table.

Here, we present the "Sleep Open-source Muscle Activity analysis Software" (SOMAS). SOMAS is an open-source and open-access tool that allows automatic quantification of muscle activity across different sleep stages with atonia [5,6] and DNE [15] indexes and with LM and periodicity indices according to the WASM 2016 rules [18].

2. Materials and methods

2.1. Software description

This section presents an overview of the main characteristics of SOMAS. Fig. 1 presents a workflow of our proposed software, and the detailed manual of installation and operation is provided as Supplemental Material. It must be emphasized that SOMAS is intended for educational and research use only and is not a certified medical software. It must not therefore be used for diagnosis, clinical decision-making, or patient care. Table 3 summarizes the main features of SOMAS.

2.1.1. System requirements, installation, and supported file formats

SOMAS was programmed in MATLAB (version R2025a, MathWorks, Natick, USA) and is freely available both as standalone executable and as source code [github link: https://github.com/macesari/SOMAS]. Its use does not require any license fee, but only the installation of the MATLAB R2025a runtime, which is freely available to download on the MathWorks website [23]. Specific system requirements for the MATLAB runtime are also available online [24]. SOMAS accepts data in European Data Format + (EDF+), a format which is widely used in sleep medicine and supported by most polysomnographic (PSG) software. SOMAS operates on local computers, without any online data sharing.

2.1.2. Settings specifications

Through a series of user interfaces, the user is asked to specify settings which are needed for the correct execution of SOMAS.

First, the user has the possibility to select the analysis window where the desired analyses should be performed (i.e., the whole recording or a part of it). At a minimum, relevant sleep stage scoring information

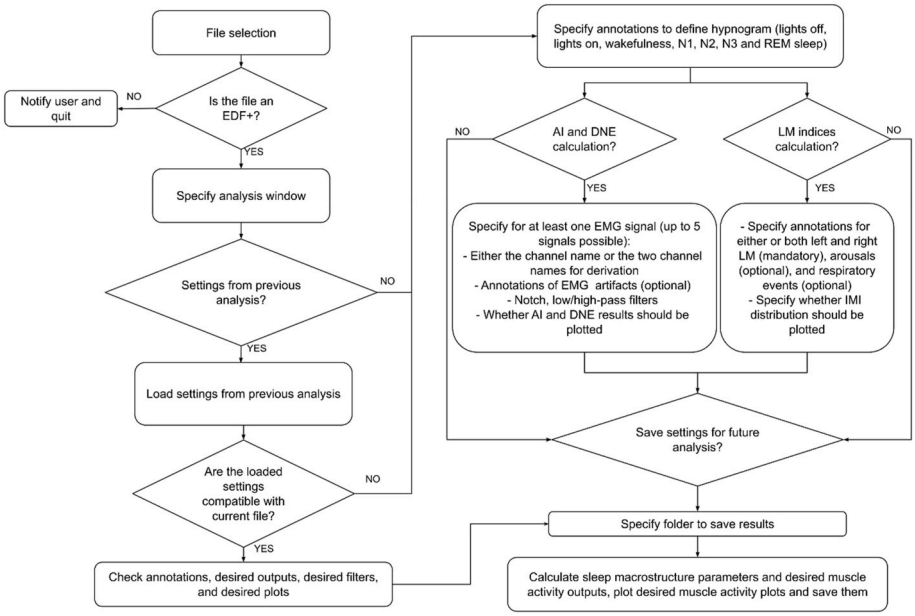

Fig. 1. Overview of the structure of SOMAS. AI: atonia index; DNE: distribution of normalized EMG values; EDF+: European Data Format +; EMG: electromyography; IMI: inter-movement interval; LM: limb movement.

Table 3
Main features of SOMAS
EDF+: European Data Format +; EMG: electromyography; IMI: inter-movement interval; LM: leg movement; NREM: non-REM; REM: rapid eye movement; W: wakefulness.

Feature	Description
Repository link	https://github.com/macesari/SOMAS
Bug report	Bugs/issues can be reported in https://github.com/macesari/SOMAS/issues
System requirements	Requires installation of Matlab 2025a Runtime (link)
Input data	EDF+ format
Minimum required inputs from user	Selection of analysis window Relevant sleep stage scoring information (lights off/on and sleep stages)
Inputs required from user for calculation of atonia indices and DNE	EMG channel mapping (Optionally) Artifacts annotations to exclude parts of signals from analyses Filters (notch and/or low/high-cut) Tick box for result visualization
Inputs required from user for calculation of LM indices according to the WASM criteria	Annotations of LM on the left and/or right side (Optionally) Annotations of respiratory events and arousals Tick box for visualization of IMI histograms
Outputs	(Always) Sleep macrostructure parameters Atonia indices in W, N1, N2, N3, NREM and REM sleep and relative graphs for the selected EMG channels, according to the inputs provided by the user 1st, 3rd, 5th, 25th, 50th, 75th, 95th, 97th and 99th percentiles of normalized EMG in W, N1, N2, N3, NREM and REM sleep and relative graphs for the selected EMG channels, according to the inputs provided by the user Details on scored LM, LM periodicity indices and IMI histogram, according to the inputs provided by the user.
Processing of multiple files	Not possible in order to minimize possible user errors. The user can, however, save all the specified settings (i.e., annotations, EMG channel mapping, filters, etc.) for efficient processing of additional files.
Usage of SOMAS	SOMAS IS INTENDED FOR EDUCATIONAL AND RESEARCH PURPOSES ONLY AND IS NOT A CERTIFIED MEDICAL DEVICE. IT MUST NOT THEREFORE BE USED FOR DIAGNOSIS, CLINICAL DECISION-MAKING OR PATIENT CARE.

(including lights off/on and sleep stages) must be embedded as annotations in the EDF+ file. The user selects these annotations through a graphical interface, thus no proprietary annotation format conversion is required.

SOMAS allows calculation of the atonia indices [5,6] and DNE [15] in up to five EMG signals e.g., chin, left arm, right arm, left leg and right leg. Because EMG channel mapping structures vary between PSG systems, the user can adapt such mapping within the interface to match their laboratory's conventions. Filters applied to the EMG signals can also be selected by the user. The notch filter (either at 50 or 60 Hz) is implemented as a zero-phase second-order infinite impulse response filter with Q factor set to 30. Low- and high-cut filters are implemented as 6th order zero-phase Butterworth filters. For the calculation of the atonia indices [5,6] and DNE [15], SOMAS allows the user to exclude parts of the EMG signals containing artifacts. Artifact annotations should be prepared in the EDF+ file beforehand using a unique label for each EMG signal. Finally, the user has the option to choose whether they want to visualize the obtained values of the atonia and DNE indices graphically.

To calculate LM indices according to the WASM criteria [20], the user is required to specify the annotations for LM on the left and/or right side. Annotations for arousals and respiratory events can also be optionally defined. The user can also choose whether they would like to visualize the distribution of the inter-movement intervals (IMI). It should be remarked that SOMAS does not score candidate LM starting from the raw EMG signal, but rather starting from candidate LM annotations embedded in the input EDF+ file.

The user must finally specify the folder where the results should be saved.

2.1.3. Computations and outputs

Once all the necessary settings for the desired analyses are defined, the user can start computations.

2.1.3.1. Sleep macrostructure. By default, SOMAS calculates a set of sleep macrostructure metrics (Table S1), which are saved in a .csv file.

2.1.3.2. Atonia indices computation. The atonia indices are computed according to the original published descriptions [5,6]. The computation is performed in the analysis window selected by the user, between lights off and lights on, and excluding the signal-specific artifacts identified by the user. The following steps are followed for each specified EMG signal: 1) the signal is filtered with the filters defined by the user; 2) the signal is rectified; 3) average values of the rectified signal are calculated in non-overlapping 1-s windows; 4) the effects of noise are reduced by removing, for each 1-s window, the minimum value in the surrounding 60-s window; 5) for each sleep stage, the percentage of noise-corrected averaged and rectified 1-s windows with amplitude ≤ 1 μV ($P_{[0,1]}$) and of those with amplitude > 1 μV and ≤ 2 μV ($P_{(1,2]}$) is calculated; 6) the atonia indices are computed as $P_{[0,1]}/(100- P_{(1,2]})$. The values of atonia index for each sleep stage and for each EMG channel specified by the user are saved in a.csv file. By default, the results include also the average atonia index across legs and/or arms.

2.1.3.3. DNE computation. DNE is computed according to the original published description [15] in the analysis window selected by the user, between lights off and lights on, and excluding the signal-specific artifacts identified by the user. The computation is performed with the following steps: 1) the signal is filtered with the filters defined by the user; 2) the signal is rectified; 3) the signal is averaged (*raEMG*) in windows of 0.5 s; 4) the bottom and top 0.5% of the *raEMG* values are discarded; 5) each *raEMG* value is normalized in the range 0–100, by applying the formula

$$EMG_{norm} = 100 \cdot \frac{raEMG - \min(raEMG)}{\max(raEMG) - \min(raEMG)}$$

6) for each sleep stage, as a descriptor of the distribution of the normalized EMG (DNE) values, the 1st, 3rd, 5th, 25th, 50th, 75th, 95th, 97th and 99th percentiles of EMG_{norm} are computed and saved in a .csv file. By default, the results include also the average of DNE centiles across legs and/or arms.

2.1.3.4. Computation of LM indices. Based on the LM (and optionally arousals and/or respiratory events) annotations provided by the user, LM indices are calculated according to the WASM 2016 criteria [20] as detailed in Table S2. These LM indices values are saved in a .csv file. Three additional .csv files containing the IMI distribution and detailed information for each LM are also saved.

2.1.4. Processing of multiple files

SOMAS is designed to process one file at a time to ensure that differences in recording protocols or annotation formats between files do not lead to unnoticed analysis errors. To improve efficiency, users can

Table 4
Demographic and sleep information of the subjects included in the study.
AHI: apnea-hypopnea index; iRBD: isolated REM sleep behavior disorder; REM: rapid eye movement; RWA: REM sleep without atonia; SINBAR: sleep Innsbruck Barcelona; SL: sleep latency; TRT: total recording time; TST: total sleep time; WASO: wake after sleep onset.

Parameter	iRBD	RLS	SDB	Controls
Number	8	5	7	5
Males [%]	100.0	20.0	57.1	80.0
Age [years]	63.3 ± 9.4	50.2 ± 21.8	67.6 ± 14.3	47.0 ± 13.1
TRT [min]	474.8 ± 16.8	491.8 ± 15.9	484.3 ± 47.4	471.4 ± 17.3
TST [min]	391.9 ± 43.7	422.1 ± 63.4	415.0 ± 69.5	397.6 ± 53.6
SL [min]	17.3 ± 11.5	16.4 ± 16.4	12.6 ± 8.2	36.8 ± 23.9
WASO [min]	65.6 ± 36.3	53.3 ± 53.6	56.7 ± 36.7	37.1 ± 27.4
N1 [%TST]	13.6 ± 4.7	12.4 ± 3.3	14.1 ± 9.1	6.5 ± 1.9
N2 [%TST]	61.2 ± 11.9	54.9 ± 4.8	48.7 ± 11.1	52.7 ± 13.1
N3 [%TST]	9.3 ± 7.1	11.3 ± 6.9	16.5 ± 13.7	19.5 ± 7.6
REM [%TST]	15.9 ± 6.2	21.4 ± 2.4	20.7 ± 6.7	21.3 ± 7.4
AHI [/h]	3.9 ± 4.4	5.6 ± 4.5	5.4 ± 4.4	1.1 ± 0.9
AHI in REM [/h]	3.9 ± 4.7	4.6 ± 5.4	2.0 ± 2.8	1.7 ± 2.1
RWA according to SINBAR [%]	59.2 ± 17.3	12.4 ± 8.2	14.4 ± 8.3	14.3 ± 6.5

save analysis settings (see Section 2.1.2) from one session and reload them for subsequent analyses, adjusting them as needed for each file.

2.2. Beta-testing

During the development, SOMAS underwent a round of beta-testing involving sleep medicine researchers in different countries. The beta testers were asked to test the software on their own data, giving feedback on possible software malfunctions and on their user experience. Although we did not quantitatively evaluate user-friendliness with validated scales, this helped us design SOMAS in a way that it can be easily used without any programming experience.

2.3. Application of SOMAS

2.3.1. Dataset

A total of 25 subjects who underwent video-PSG (v-PSG) at the Center for Sleep Medicine, Department of Neurology, Medical University of Innsbruck, Austria, were included. V-PSG included recording of the electroencephalogram (F2, F4, C2, C4, O1, O2, M1 and M2 channels), electrooculogram (horizontal and vertical), EMG (mentalis and submentalis muscles, bilateral flexor digitorum superficialis -FDS- and tibialis anterior -AT- muscles), one electrocardiographic lead, and respiratory channels according to international criteria [25]. EMG signals were acquired with sampling frequency of 1000 Hz (17 subjects) and 1024 Hz (eight subjects). Sleep stages, arousals (only for eight subjects) and respiratory events were manually scored for all subjects according to international criteria [25]. Candidate LM were automatically detected with a validated software and provided as input as annotations embedded in the EDF+ files together with wake-sleep state scoring [26].

The subjects included eight patients with a diagnosis of iRBD, five patients with RLS, seven patients with sleep-disordered breathing (SDB), and five clinical controls, i.e., subjects who underwent a v-PSG and for whom no relevant sleep disorder was identified. One patient with iRBD and one patient with SDB had RLS as a secondary diagnosis. Furthermore, six patients with iRBD and two with RLS had also a secondary diagnosis of SDB. Diagnoses were established according to the third edition of the International Classification of Sleep Disorders [27] and iRBD diagnosis adhered also to recent guidelines [28]. RWA was quantified semi-automatically according to the Sleep Innsbruck Barcelona (SINBAR) criteria in 3-s mini-epochs [8,9]. Table 4 reports demographic and sleep information of the subjects included in the study.

This retrospective analysis was approved by the Ethics committee of the Medical University of Innsbruck (1054/2020).

2.3.2. Data analyses

The accuracy of SOMAS to derive the atonia indices and to compute LM indices was assessed by comparing its outputs to the ones derived by Hypnolab [4], which is the only non-open-source software that can calculate these indices. To our knowledge, no published software providing DNE computation is available.

The atonia indices were calculated by using both SOMAS and Hypnolab in all sleep stages and for each of the five EMG signals recorded. EMG signals were filtered with a notch filter at 50 Hz and with low-cut and high-cut filters at 10 Hz and 100 Hz, respectively. As Hypnolab does not allow removal of artifacts for calculation of atonia indices, artifacts were not excluded for this computation in SOMAS. Moreover, LM indices (Table S2) were computed according to the WASM criteria [18] by employing the annotations of LM, arousals, and respiratory events using both SOMAS and Hypnolab. Spearman correlation coefficients, their relative p-values, and Bland-Altman plots were used to evaluate the agreement between SOMAS and Hypnolab.

To demonstrate that SOMAS achieves its intended purpose, the atonia indices and the centiles of DNE in REM sleep for submentalis, FDS, and AT muscles were compared between the patients with iRBD and the remaining subjects. The atonia indices and DNE were computed

Table 5
Comparison of atonia index values between SOMAS and Hypnolab
FDS: flexor digitorum superficialis; IQR: inter-quartile range; REM: rapid eye movement; W: wakefulness. ***: $P < 0.001$.

Muscle	Sleep stage	Hypnolab (mean ± std)	SOMAS (mean ± std)	Spearman ρ	Bias (median [IQR])	Relative bias (median [IQR]) [%]
Submentalis	W	0.35 ± 0.19	0.37 ± 0.19	0.998***	−0.015 [-0.018,-0.010]	−4.4 [-5.8,-3.7]
	N1	0.50 ± 0.23	0.52 ± 0.23	0.996***	−0.013 [-0.019,-0.010]	−2.5 [-5.5,-1.6]
	N2	0.75 ± 0.24	0.76 ± 0.23	0.997***	−0.007 [-0.012,-0.003]	−0.9 [-1.8,-0.3]
	N3	0.78 ± 0.34	0.85 ± 0.24	0.995***	−0.002 [-0.004,-0.001]	−0.2 [-0.5,-0.1]
	REM	0.83 ± 0.23	0.84 ± 0.23	0.999***	−0.005 [-0.010,-0.003]	−0.6 [-1.3,-0.3]
FDS – left	W	0.76 ± 0.11	0.78 ± 0.10	0.974***	−0.012 [-0.028,-0.009]	−1.8 [-3.9,-1.2]
	N1	0.92 ± 0.04	0.94 ± 0.03	0.965***	−0.007 [-0.014,-0.004]	−0.8 [-1.6,-0.4]
	N2	0.96 ± 0.04	0.97 ± 0.03	0.963***	−0.003 [-0.005,-0.002]	−0.3 [-0.5,-0.2]
	N3	0.89 ± 0.28	0.98 ± 0.02	0.906***	−0.002 [-0.005,-0.001]	−0.2 [-0.5,-0.1]
	REM	0.92 ± 0.09	0.93 ± 0.08	0.982***	−0.005 [-0.011,-0.002]	−0.6 [-1.3,-0.2]
FDS – right	W	0.73 ± 0.14	0.75 ± 0.13	0.995***	−0.014 [-0.023,-0.007]	−2.0 [-3.9,-0.9]
	N1	0.93 ± 0.05	0.93 ± 0.04	0.994***	−0.006 [-0.009,-0.003]	−0.7 [-1.0,-0.3]
	N2	0.97 ± 0.02	0.97 ± 0.02	0.996***	−0.002 [-0.004,-0.001]	−0.2 [-0.4,-0.1]
	N3	0.89 ± 0.28	0.98 ± 0.03	0.994***	−0.001 [-0.002,0.000]	−0.1 [-0.2,-0.0]
	REM	0.93 ± 0.08	0.94 ± 0.08	0.994***	−0.004 [-0.009,-0.002]	−0.4 [-1.0,-0.2]

Table 6
Comparison of leg movement indices between SOMAS and Hypnolab
Avg: average; dur: duration; LM: leg movement; PLMS and PLMW: periodic LM during sleep and wakefulness, respectively; ILMS and ILMW: isolated LM during sleep and wakefulness, respectively; SILMS and SILMW: short-interval leg movements during sleep and wakefulness, respectively; REM: rapid-eye-movement sleep; NREM: non-REM. *: $P < 0.001$.

Parameter	Hypnolab (mean ± std)	SOMAS (mean ± std)	Spearman ρ	Bias (median [IQR])	Relative bias (median [IQR]) [%]
PLMS index [/h]	26.4 ± 29.1	26.7 ± 29.3	1.000***	−0.145 [-0.419, −0.042]	−1.1 [-1.4, −0.6]
PLM index, NREM [/h]	7.8 ± 14.2	7.9 ± 14.4	1.000***	−0.011 [-0.055, 0.000]	−1.1 [-1.4, −0.7]
PLM index, REM [/h]	30.5 ± 34.5	30.8 ± 34.7	0.999***	−0.192 [-0.519, −0.105]	−1.1 [-1.4, −0.8]
PLMW index [/h]	29.9 ± 18.9	30.1 ± 19.0	0.999***	−0.281 [-0.517, −0.104]	−1.3 [-1.6, −0.9]
PLMS arousal index [/h]	5.9 ± 10.2	6.0 ± 10.2	1.000***	−0.007 [-0.06, −0.001]	−0.9 [-2.0, −0.7]
SILMS index [/h]	5.4 ± 5.1	5.5 ± 5.2	0.999***	−0.043 [-0.087, −0.010]	−0.9 [-1.8, −0.3]
SILMW index [/h]	29.3 ± 23.0	29.8 ± 23.3	1.000***	−0.263 [-0.788, −0.127]	−1.3 [-1.8, −0.9]
ILMS index [/h]	10.5 ± 4.1	10.7 ± 4.2	1.000***	−0.127 [-0.169, −0.068]	−1.2 [-1.4, −0.8]
ILMW index [/h]	31.3 ± 12.4	31.8 ± 12.4	0.997***	−0.374 [-0.637, −0.235]	−1.1 [-1.6, −1.0]
Avg. dur PLMS [s]	2.3 ± 0.8	2.3 ± 0.8	0.989***	0.009 [-0.020, 0.025]	0.3 [-0.9, 1.1]
Avg. dur PLMW [s]	3.8 ± 1.3	3.8 ± 1.3	0.998***	0.003 [-0.023, 0.021]	0.1 [-0.6, 0.4]
Avg. dur SILMS [s]	2.4 ± 0.6	2.4 ± 0.6	0.996***	0.002 [-0.019, 0.017]	0.1 [-0.7, 0.8]
Avg. dur SILMW [s]	3.4 ± 1,0	3.4 ± 0.9	0.997***	−0.016 [-0.031, 0.031]	−0.6 [-1.2, 0.7]
Avg. dur ILMS [s]	2.7 ± 0.6	2.7 ± 0.6	0.997***	0.002 [-0.026, 0.017]	0.1 [-1.0, 0.7]
Avg. dur ILMW [s]	3.8 ± 1.1	3.8 ± 1.0	0.99***	−0.002 [-0.015, 0.023]	−0.0 [-0.5, 0.6]
PLMS index (left LM) [/h]	11.7 ± 18.2	11.8 ± 18.3	1.000***	−0.050 [-0.208, −0.029]	−1.2 [-2.2, −0.8]
PLMW index (left LM) [/h]	8.29 ± 6.9	8.4 ± 6.9	0.999***	−0.082 [-0.120, −0.007]	−1.1 [-1.6, −0.6]
PLMS index (right LM) [/h]	9.3 ± 10.1	9.4 ± 10.2	0.999***	−0.065 [-0.170, −0.027]	−1.3 [-1.8, −0.9]
PLMW index (right LM) [/h]	8.8 ± 6.5	8.9 ± 6.6	1.000***	−0.067 [-0.150, −0.030]	−1.1 [-1.8, −0.8]
PLMS index (bilateral LM) [/h]	5.4 ± 6.8	5.5 ± 6.8	1.000***	−0.042 [-0.070, 0.000]	−1.1 [-2.2, −0.2]
PLMW index (bilateral LM) [/h]	12.8 ± 8.6	12.8 ± 8.7	0.995***	−0.124 [-0.214, −0.037]	−1.1 [-1.3, −0.6]
Periodicity index in sleep	0.49 ± 0.3	0.5 ± 0.3	0.999***	0.000 [0.000, 0.000]	−0.0 [-0.1, 0.0]
Periodicity index in wakefulness	0.3 ± 0.1	0.3 ± 0.1	0.997***	0.000 [0.000, 0.000]	0.0 [-0.1,0.1]

with SOMAS after removing artifacts and filtering the EMG signals with a notch filter at 50 Hz and with low-cut and high-cut filters at 10 Hz and 100 Hz, respectively. The ability to differentiate patients with iRBD from the remaining subjects based on each atonia index value and DNE centile was evaluated by means of the area under the receiver operating characteristic (ROC) curve (AUC). Finally, for the same purpose, AUC was calculated to differentiate patients with RLS from controls based on the PLMS and periodicity indices. In addition, the distributions of IMI were compared between patients with RLS and control subjects with Mann-U-Whitney tests.

In all analyses, data were reported as means ± standard deviation except for data on bias, which were reported as medians [interquartile range], and p-values were considered significant when below 0.05.

3. Results

Table 5 and Table S3 report the agreement in the values of atonia index for all muscles and sleep stages computed between Hypnolab and SOMAS. The atonia index values calculated by SOMAS tended to be slightly higher than those computed by Hypnolab, but the two software showed very high agreement in all comparisons: the Spearman correlation coefficients were >0.97 in 24/25 comparisons, and the median modulus of the absolute bias was <0.02 in 23/25 comparisons.

Table 6 reports the agreement in the values of the LM indices between Hypnolab and SOMAS. Also in this case, SOMAS showed an excellent agreement with Hypnolab for the calculated values: all correlation coefficients were >0.99 and the modulus of the relative bias was <1.5%.

Fig. 2 reports the distributions of the atonia indices in REM sleep for the submentalis, FDS, and AT muscles in the eight patients with iRBD and the remaining 17 subjects not diagnosed with RBD, as well as the ROC curves and relative AUC values. The best AUC value (0.993) was obtained when considering the average atonia index between the FDS muscles. Fig. 3 shows the distribution of the DNE centiles during REM sleep in patients with iRBD and the remaining subjects. For each muscle, only the ROC curve of the centile leading to the highest AUC is reported. In this case, the 97th centile of the DNE averaged over the AT muscles achieved perfect discrimination between the groups.

Finally, SOMAS indicated that patients with RLS had higher PLMS index than controls (30.3/h ± 39.1/h vs. 4.2/h ± 5.5/h) as well as higher periodicity index during sleep (0.51 ± 0.33 vs. 0.25 ± 0.25). These indices differentiated patients with RLS from controls with AUC of 0.750 and 0.714, respectively. Fig. 4 shows the distribution of the number of LM during sleep as a function of the IMI. Patients with RLS had significantly more LM than controls for several IMI values, with a first peak at 3 s and a second main peak at 15–17 s.

4. Discussion

We developed SOMAS, the first open-access, open-source software capable of analyzing muscle tone and sleep-related movements from EDF+ files, implementing both the atonia index [5,6] and the DNE [15] alongside LM indices calculated according to the WASM 2016 criteria [18]. By design, SOMAS addresses limitations of existing tools by accepting EDF+ files generated by different PSG systems, providing flexible artifact exclusion, and making the underlying code freely available for adaptation and further development.

In comparison with established non-open-source solutions such as Hypnolab and RBDtector, SOMAS eliminates the need for proprietary annotation formats, allowing direct use of EDF+ embedded annotations

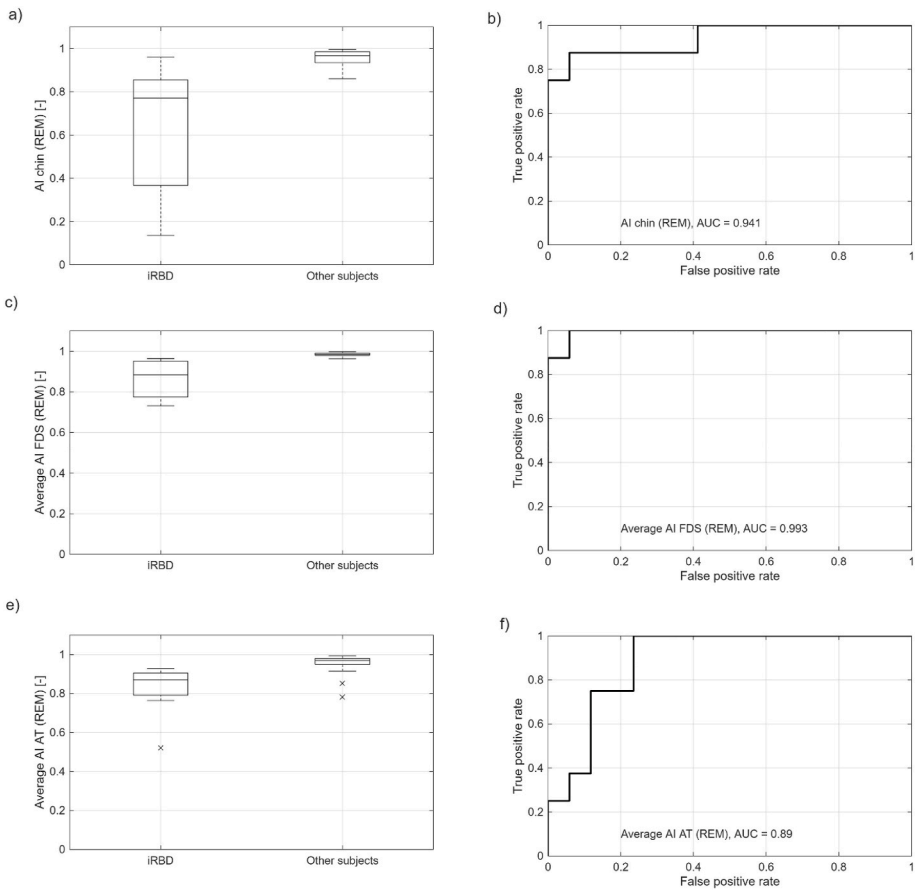

Fig. 2. Values of the atonia index during rapid-eye-movement sleep in patients with isolated REM sleep behavior disorder. Panels a), c), and e) show boxplots of the distribution of the atonia index (AI) during rapid-eye-movement (REM) sleep for patients with isolated REM sleep behavior disorder (iRBD, n = 8) and all other subjects (n = 17) for the chin (i.e., submentalis) muscle, the flexor digitorum superficialis (FDS) muscles, and the anterior tibialis (AT) muscle respectively. For the upper and lower extremities, the average values of AI over left and right limbs were used. Outliers are plotted individually using the 'x' marker symbol. Panels b), d), and f) show the receiver operating characteristic (ROC) curves obtained to discriminate patients with iRBD from all other subjects based on the chin (i.e. submentalis) AI, the average AI across FDS muscles, and the average AI across AT muscles, respectively. In each plot, the area under the curve (AUC) is reported.

through an intuitive interface. Its capacity to exclude signal-specific artifacts is a practical advantage for research applications where noise handling is critical. While batch processing was intentionally excluded to reduce the risk of unnoticed inconsistencies between files, the option to reuse saved settings still facilitates efficient analysis of multiple datasets.

SOMAS is currently intended for educational and research use only and is not registered as a medical device. Nevertheless, by publishing its complete source code, we enable the community to expand its functionalities, for example by integrating RWA computation according to the SINBAR criteria [8], as recommended in current guidelines [28]. The atonia index and DNE outputs can be computed beyond REM sleep, potentially supporting novel investigations into muscle activity patterns across all sleep stages.

Although implemented in MATLAB, the availability of the code allows straightforward translation to fully open-source environments such as Python. The stand-alone executable further ensures accessibility for users without a MATLAB license, broadening its potential uptake among researchers with varying technical expertise.

The proof-of-concept application in this study, despite a relatively small sample, demonstrated strong agreement with Hypnolab for atonia index and LM indices and confirmed the expected ability of atonia indices and DNE to differentiate patients with iRBD from other groups, as well as the capacity of PLMS and periodicity indices to differentiate patients with RLS from controls. These findings, consistent with previous literature, support the reliability and applicability of SOMAS for quantitative research on muscle activity during sleep.

Our study has limitations. First, as previously pointed out, we analyzed data from a limited number of subjects. Future analyses with SOMAS should include not only larger samples, but also patients with other conditions and of different age groups. Second, although EDF+ files are generated according to guidelines and we performed a round of beta-testing of SOMAS on EDF+ files generated by different PSG software, inconsistencies may occur with files generated by other sources, possibly precluding the analysis with SOMAS. In the repository where SOMAS is shared, users have the possibility to inform us on possible issues, so that we can efficiently solve them. Finally, SOMAS allows users to specify EMG artifacts that should be removed from analyses. In some cases, however, identification of EMG artifacts has significant inter-rater variability [1]. Future studies with SOMAS should carefully

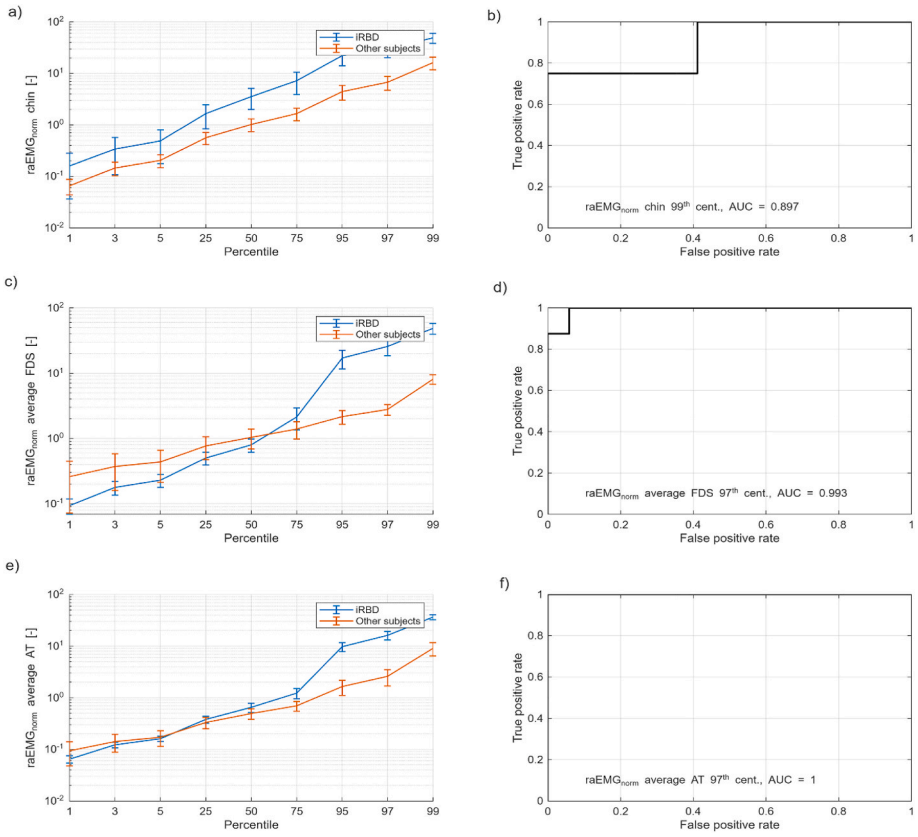

Fig. 3. Distribution of the normalized electromyographic activity during rapid-eye-movement sleep in patients with isolated REM sleep behavior disorder. Panels a), c), and e) show the distributions of normalized electromyographic activity (DNE) during rapid-eye-movement (REM) sleep for patients with isolated rapid-eye-movement sleep behavior (iRBD, n = 8) and the remaining subjects (n = 17) for the chin (i.e., submentalis) muscle, the flexor digitorum superficialis (FDS) muscles, and the anterior tibialis (AT) muscle respectively. For the upper and lower extremities, the average values of left and right limbs are shown. Data are shown as means and standard deviation. Panels b), d), and f) show the best receiver operating characteristic (ROC) curves obtained to separate the two groups using the DNE for the chin (i.e. submentalis) muscle, the average DNE of FDS muscles, and the average DNE of AT muscles. In each plot the centile leading to the highest area under the curve (AUC) and the AUC value itself are reported.

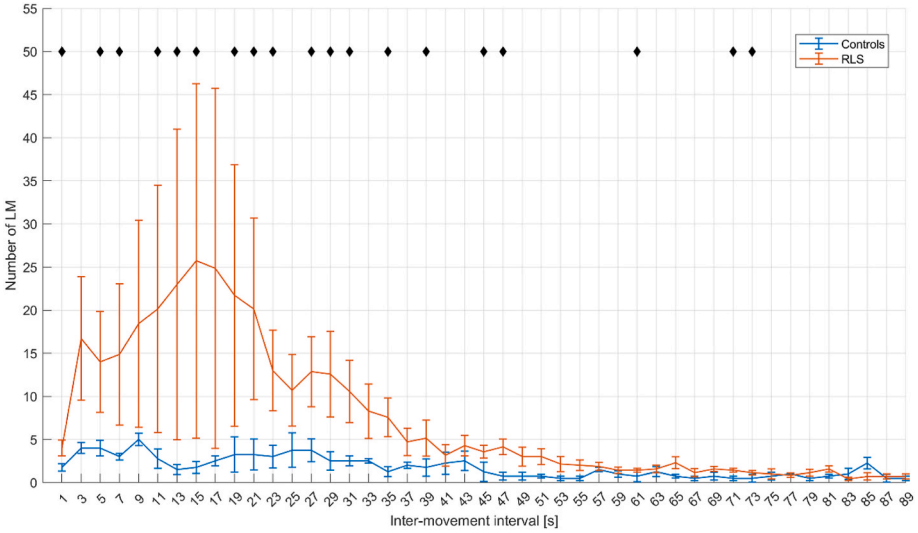

Fig. 4. Distribution of inter-movement intervals. Distributions of the number of leg movements (LM) as a function of their inter-movement intervals are shown for patients with the restless legs syndrome (RLS, n = 7) and control subjects (n = 5). Intervals for which a significant difference was obtained between groups are marked with a diamond on top of the graph. Data are shown as mean and standard deviation.

evaluate the robustness to recording artifacts of the different indexes of muscle activity during sleep.

In conclusion, SOMAS combines methodological rigor, interoperability, and open accessibility, offering the sleep research community a robust platform for standardized and reproducible analyses of muscle activity. By fostering transparency and facilitating collaborative development, it has the potential to advance both the methodological and translational aspects of sleep-related movement disorder research.

CRediT authorship contribution statement

Matteo Cesari: Writing – original draft, Validation, Software, Methodology, Formal analysis, Conceptualization. **Raffaele Ferri:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Birgit Högl:** Writing – review & editing, Resources, Conceptualization. **Ambra Stefani:** Writing – review & editing, Resources, Conceptualization. **Alessandro Silvani:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sleep.2026.108791.

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