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(Article begins on next page)

An Open-Source Toolbox for Enhancing the Assessment of Muscle Activation Patterns

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Abstract

Dynamic muscle activity can be quantitatively and non-invasively investigated during several cyclical movements by acquiring surface electromyographic (sEMG) signals. The accurate temporal analysis of muscle activations is of great importance in several research areas spanning from the assessment of altered muscle activation patterns in orthopaedic and neurological patients to the monitoring of their motor rehabilitation. Several studies have highlighted the challenge of understanding and interpreting muscle activation patterns due to the high cycle-by-cycle variability of the sEMG data. This makes it difficult to interpret results and to use sEMG signals in the clinical practice. To overcome this limitation, specific algorithms are needed to help scientists to easily characterize and assess muscle activation patterns during cyclical movements. In this perspective, *CIMAP* (Clustering for the Identification of Muscle Activation Patterns) is an open-source Python toolbox based on agglomerative hierarchical clustering that aims at characterizing muscle activation patterns during cyclical movements by grouping movement cycles showing similar muscle activity. From muscle activation intervals to the graphical representation of the agglomerative hierarchical clustering dendrograms, the proposed toolbox offers a complete analysis framework for enabling the assessment muscle activation pattern. The toolbox can be flexibly modified to comply with the necessities of the scientist. *CIMAP* is addressed to scientists of any programming skill level working in different research areas such as biomedical engineering, robotics, sports, clinics, biomechanics, and neuroscience. *CIMAP* is freely available on GitHub (<https://github.com/Biolab-PoliTO/CIMAP>).

Keywords: clustering, cyclical movements, EMG, machine learning, muscle activation patterns.

1. Introduction

Surface electromyography (sEMG) is commonly used, in several research areas, to quantitatively and non-invasively assess dynamic muscle activity in both physiological and pathological conditions. Among the most studied sEMG-derived parameters, the identification of the onset and offset instants of muscle activity plays a fundamental role. The assessment of sEMG activation intervals achieved great interest among researchers in a wide variety of clinical,

robotic, and sports applications. In particular, muscle activation intervals are used to assess altered sEMG patterns in patients affected by orthopaedic or neurological diseases (Hsu *et al* 2019, Castagneri *et al* 2019), to define rehabilitation protocols tailored to the patient needs (Akef Khowailed and Abotabl 2019), to study posture control (Labanca *et al* 2021), to control prostheses and exoskeletons (Micera *et al* 2010, Li *et al* 2023), and to evaluate return-to-sport of athletes after injury (Rocchi *et al* 2020).

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3 However, sEMG signals during gait are characterized by
4 high cycle-by-cycle variability that makes it difficult to
5 interpret the results and to use sEMG data in clinical practice
6 (Agostini *et al* 2020, Winter and Yack 1987). For a specific
7 muscle of a subject, different activation patterns are usually
8 assessed during cyclical movements, each of them
9 characterized by a specific frequency of occurrence (Di Nardo
10 *et al* 2017). Considering the walking task, even in healthy
11 subjects, a single muscle does not show a single preferred
12 pattern of activation, but up to 4-5 distinct sEMG patterns,
13 each characterized by a different number of activation
14 intervals occurring within the stride (Agostini *et al* 2010,
15 2015). To overcome this limitation, specific algorithms are
16 needed to help scientists to easily characterize and assess
17 muscle activation patterns during cyclical movements.

18
19 Cluster analysis may represent a useful tool for helping
20 scientists to study the different muscle activation patterns
21 during cyclical movements. In this perspective, *CIMAP*
22 (Clustering for the Identification of the Muscle Activation
23 Patterns) algorithm was proposed and validated in different
24 healthy and pathological conditions (Rosati *et al* 2017a,
25 2017b). The *CIMAP* algorithm is based on agglomerative
26 hierarchical clustering and aims at characterizing muscle
27 activation patterns during cyclical movements by grouping
28 movement cycles showing similar muscle activity. It was
29 specifically developed to assess muscle activity patterns
30 during walking in both physiological and pathological
31 conditions and it was successfully applied to the study of gait
32 asymmetry in healthy, orthopaedic, and neurological patients
33 (Castagneri *et al* 2019, Rosati *et al* 2021). Moreover, the study
34 by Ghislieri *et al.* used the *CIMAP* algorithm as a pre-
35 processing step before muscle synergy extraction to evaluate
36 human motor control during locomotion (Ghislieri *et al* 2019,
37 2020). Notice that the *CIMAP* algorithm was originally
38 proposed for assessing gait in both physiological and
39 pathological conditions. Nevertheless, *CIMAP* can be
40 potentially applied to other cyclical movements, as cycling
41 and reach-to-grasp movements.

42
43 In this contribution, to support researchers interested in the
44 analysis of muscle activation pattern, we distribute an open-
45 source Python toolbox (*CIMAP*) that allows for obtaining all
46 the representative muscle activation patterns of a muscle. The
47 number of clusters identified by the *CIMAP* toolbox and the
48 cluster size (i.e., the number of elements belonging to the same
49 cluster), may represent meaningful information in clinics,
50 since they indicate how many sEMG patterns were found and
51 how frequently they occur during the analyzed movement
52 (Agostini *et al* 2014). The proposed toolbox adopts an object-
53 oriented programming approach that allows a clear definition
54 of a few classes incorporating data structure and data
55 processing methods, empowering researchers to easily extend
56 and customize the toolbox to meet specific data and protocol

needs. To better describe the processing pipeline and to
provide a set of practical guidelines, an example of *CIMAP*
application is presented considering sEMG signals acquired
from a lower-limb muscle of a representative healthy subject
during a 5-minute walking task.

Researchers with little coding experience will find in the
Python toolbox *CIMAP* a complete framework for the
assessment of muscle activation patterns during cyclical
movements, from the pre-processing of muscle activation
intervals to the graphical representation of the clustering
results.

2. Methods

CIMAP toolbox is implemented in Python and includes all
the required steps for performing the analysis of muscle
activation patterns. This toolbox incorporates functions for all
the analysis steps, from data preparation to the graphical
representation of the clustering results and data saving.

The following section provides a brief description of the
main steps of the *CIMAP* toolbox:

- a) *Dataset preparation*: *CIMAP* toolbox requires as input
the muscle activation intervals (i.e., the time intervals
characterized by muscle activity). From the muscle
activation intervals, the onset and offset instants are
extracted, representing the beginning and the end of
each muscle activation, respectively;
- b) *Pre-processing*: movement cycles characterized by the
same number of activation intervals occurring within
the cycle duration are grouped into sub-groups (or
“modalities”). Modalities characterized by a small
number of movement cycles ($num. cycles < Th$) are
considered as non-representative and thus discarded
from the following analyses. Based on a previous study
by Dotti *et al.* (Dotti *et al* 2021), the value of Th was
set equal to 10 movement cycles. Th value can be
easily adjusted to meet specific data needs, as a small
number of movement cycles;
- c) *Agglomerative hierarchical clustering*: considering
each modality separately, agglomerative hierarchical
clustering is applied. From a number of clusters equal
to the number of cycles belonging to the modality
under consideration (i.e., each cluster is
characterized by a single movement cycle),
agglomerative hierarchical clustering iteratively
merges the two “closest” clusters, until a single
cluster is obtained (i.e., a single cluster containing all
the movement cycles belonging to the modality
under consideration). The complete linkage method
is used to select the two “closest” clusters to be
merged, considering both Manhattan (L1 norm) and

Chebyshev (Linf norm) as distance metrics (Kaufman and Rousseeuw 1990). Thus, for each modality, agglomerative hierarchical clustering is applied twice (the first time considering L1 norm and the second time considering Linf norm as distance metric). The cutoff points of the dendrograms (i.e., the final number of clusters) are selected applying to each dendrogram the cutoff rule proposed by Rosati *et al.* (Rosati *et al* 2017b). Finally, after comparing the dendrograms obtained considering the L1 norm and Linf norm metrics, the one showing the lowest intra-cluster variability is selected for the following analyses;

- d) *Clustering analysis representation*: this toolbox includes several visualization methods that allow for the examination of data throughout the entire analysis process. In particular, dendrograms showing clustering results can be represented for each muscle and each modality, separately;
- e) *Data saving*: to increase the accessibility of results, their interpretability and interoperability, clustering results can be exported in .csv format.

Further details about the implemented Python classes and the default setting parameters are freely available on the GitHub repository (<https://github.com/Biolab-PoliTO/CIMAP>).

3. Results

This section describes all the steps involved in the analysis of muscle activation patterns of a sample dataset of sEMG data

acquired from two lower-limb muscles (left and right Lateral Gastrocnemius muscle) of a healthy subject during a 5-minute overground walking task.

The first step is the loading of muscle activation intervals contained in the sample dataset (*'input_file'*) through the *'data_reading'* function. The *'data_reading'* function can be called as follows:

```
s,muscles = CIMAP.data_reading(input_file =
input_file)
```

where *s* represents a data structure containing the muscle activation intervals to be processed through the *CIMAP* algorithm and *muscles* represents a data dictionary containing sEMG information (i.e., muscle labels, side, sensor placement, ...).

Then, the *'removeaddints'* function is called to remove (if any) outliers of muscle activation intervals (i.e., movement cycles characterized by always-ON or always-OFF muscle activation patterns). Further details about the outlier removal process can be found in the study by Rosati *et al.* (Rosati *et al* 2017b). The outlier removal process can be performed through the *'removeaddints'* function as follows:

```
s = CIMAP.removeaddints(s)
```

where *s* contains the muscle activation intervals after the outlier removal step.

Muscle activation intervals can be graphically represented using the *'actplot'* function. In the following, the *'actplot'* function is called to represent all the muscle activation

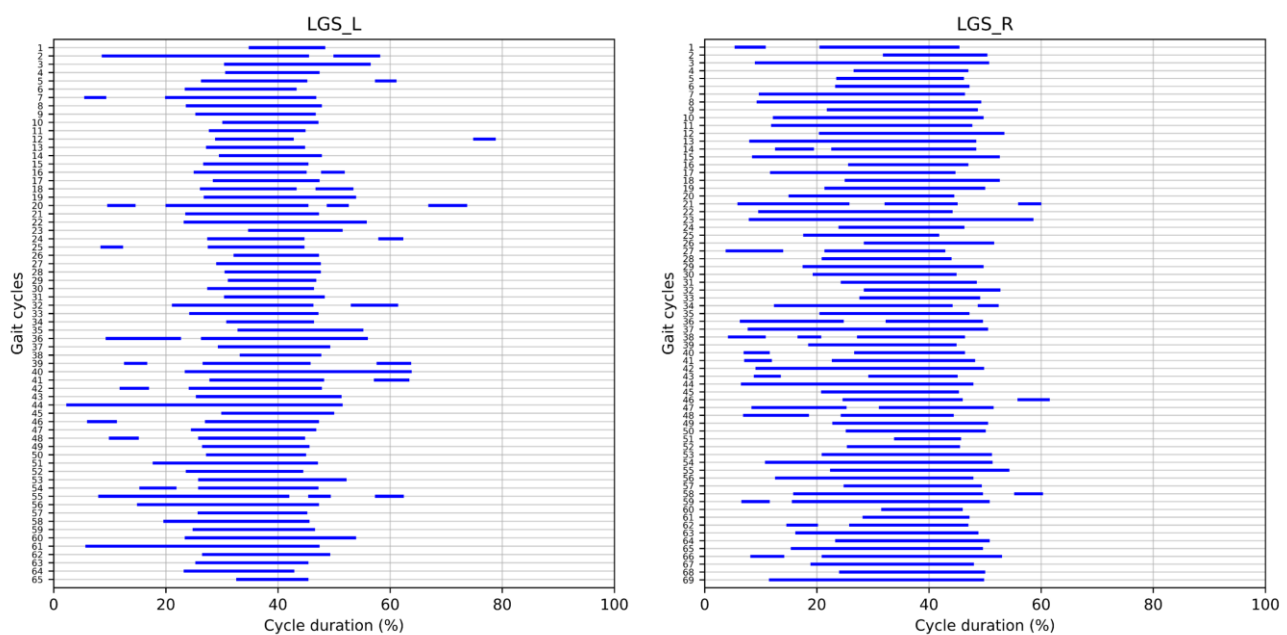


Figure 1: Example of muscle activation intervals for the left and right Lateral Gastrocnemius muscles (LGS_L and LGS_R, respectively) of a healthy volunteer during a 5-minute overground walking task. The blue horizontal lines represent muscle activation intervals expressed as a percentage of the cycle duration (BLUE = muscle active, WHITE = muscle inactive).

intervals of the left and right Lateral Gastrocnemius muscles (LGS_L and LGS_R, respectively):

```
CIMAP.actplot(s,target='LGS')
```

where s represents the data structure containing the pre-processed muscle activation intervals and $target$ is a variable containing the labels of the muscles to be represented.

Figure 1 shows the output of the `'actplot'` function considering data from the sample dataset included in the toolbox. More specifically, it represents the muscle activation intervals obtained from the left and right LGS muscles of a healthy volunteer during a 5-minute overground walking. Each horizontal blue line represents a muscle activation interval extracted from a single gait cycle expressed in percentage of cycle duration (blue = muscle active, white = muscle inactive). It can be observed that, despite intra-cycle variability, LGS muscle activity mainly occurs between 20% and 50% of the gait cycle for both the left and right sides. The muscle activation intervals included in the sample dataset were computed using the LSTM-MAD algorithm proposed by Ghislieri *et al.* (Ghislieri *et al* 2021).

Before clustering, muscle activation intervals are divided into modalities (i.e., movement cycles characterized by the same number of activation intervals occurring within the cycle duration) by using the `'modalitydivision'` function as follows:

```
muscles = CIMAP.modalitydivision(s,muscles)
```

where s contains the muscle activation intervals and $muscles$ represents the data dictionary suitable for the following clustering analysis.

To visualize the modality distribution and to assess the number of movement cycles belonging to each modality, the `'modality_distribution'` function can be used as follows:

```
CIMAP.modality_distribution(s,target='LGS')
```

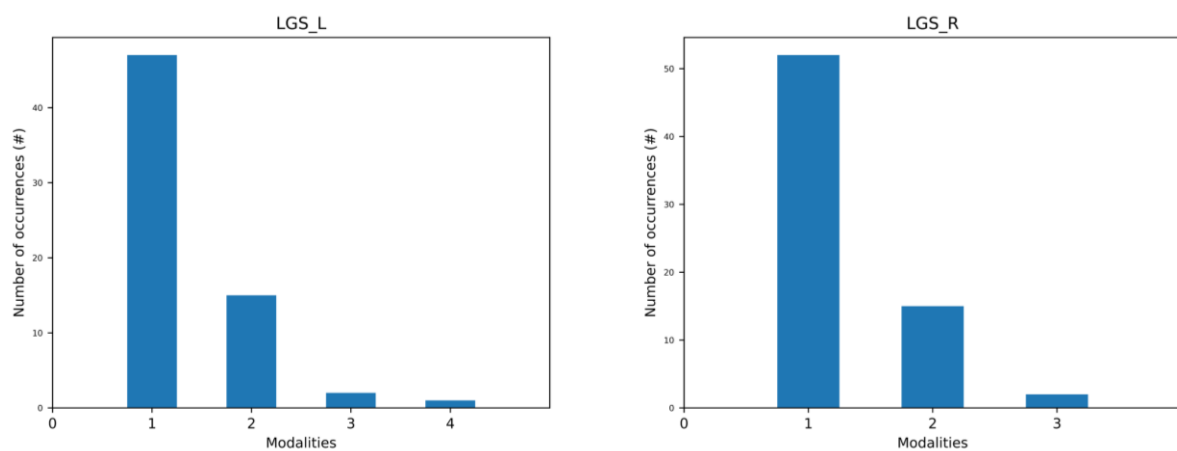


Figure 2: Histograms of movement modalities obtained from the muscle activation intervals of the left and right Lateral Gastrocnemius muscles (LGS_L and LGS_R, respectively) included in the sample dataset. Each histogram represents the number of gait cycles belonging to each modality.

where s contains the muscle activation intervals and $target$ is the variable containing the labels of the muscles to be represented.

Figure 2 shows the output of the `'modality_distribution'` function representing the histogram of the movement modalities extracted from the muscle activation intervals of the left and right Lateral Gastrocnemius muscles (LGS_L and LGS_R, respectively) included in the sample dataset. In particular, **Figure 2** shows the number of gait cycles belonging to each modality for both the left and right sides. For example, considering the right side, more than 50 gait cycles are characterized by a single muscle activation (Modality 1), approximately 15 gait cycles are characterized by 2 muscle activations (Modality 2), and less than 5 gait cycles are characterized by 3 muscle activations (Modality 3).

The agglomerative hierarchical clustering is then performed using the `'dendrograms'` function, which computes two different dendrograms by using the L1 norm and Linf norm, respectively. To select the optimal cutting point from the two dendrograms (L1 norm and Linf norm), the `'cuts'` function is applied to each dendrogram. The optimal cutting point is selected based on the rules defined by Rosati *et al.* (Rosati *et al* 2017b). The clustering analysis can be performed by calling the `'dendrograms'` and `'cuts'` functions as follows:

```
muscles = CIMAP.dendrograms(muscles)
```

```
muscles = CIMAP.cuts(muscles)
```

The `'dendrograms'` and `'cuts'` functions can be easily customized by users to meet specific data and protocol needs. The toolbox documentation available on GitHub (<https://github.com/Biolab-PoliTO/CIMAP>) includes further details on the `'dendrograms'` and `'cuts'` functions.

Clustering results can be graphically represented through the `'dendroplot'` function as follows:

```
CIMAP.dendroplot(muscles,target='LGS')
```

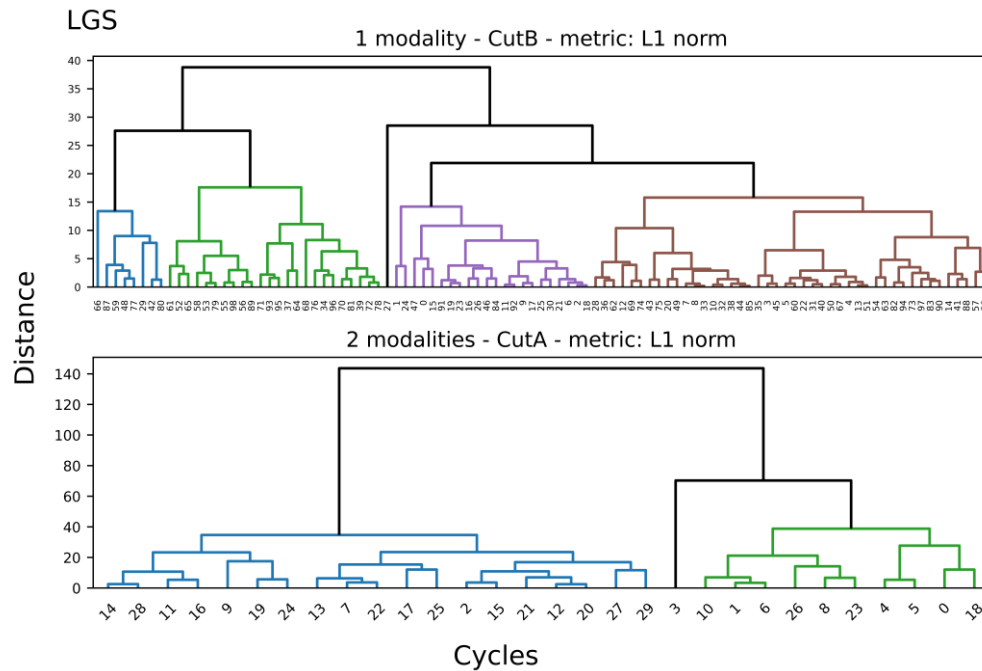


Figure 3: Agglomerative hierarchical clustering dendrograms of the sEMG activation intervals displaying a single modality (at the top) and two modalities (at the bottom). sEMG activation intervals that belong to the same cluster are represented with the same color. Both dendrograms were created using the L1 norm as the distance metric.

where *muscles* contains the clustering results obtained through the *'dendrograms'* and *'cuts'* functions and *target* is the variable containing the labels of the muscles to be represented.

Figure 3 represents the output of the *'dendroplot'* function. For each movement modality, the computed dendrograms are represented. Above each dendrogram, the specific metric and cutting point used are represented, as defined by Rosati *et al.* (Rosati *et al.* 2017b). The clusters identified after the cutting point selection are represented in different colors.

To save the CIMAP output, the *'algorithm_output'* and *'resultsaver'* functions can be called as follows:

```
cimap_out = CIMAP.algorithm_output(s,muscles)
CIMAP.resultsaver(cimap_out)
```

where *cimap_out* is a data dictionary containing the clustering results of each muscle after discarding non-significant modalities.

CIMAP results are saved in an easy-to-read and open-source format (.csv). More specifically, results are in a $M \times (C + 1)$ matrix, where M represents the number of muscles and C the total number of cycles. Notice that the first column should contain the labels of each muscle as defined in the input file.

Finally, the sEMG activation intervals clustering computed through *CIMAP* can be represented using the *'clusterplot'* function as follows:

```
CIMAP.clusterplot(cimap_out,target='LGS',
color = True)
```

where *cimap_out* is a data dictionary containing the clustering results and *target* is the variable containing the labels of the muscles to be represented. The toolbox documentation freely available on GitHub (<https://github.com/Biolab-PoliTO/CIMAP>) includes further details on the *'clusterplot'* function.

Figure 4 shows the clustering of the sEMG activation intervals computed through *CIMAP*. The sEMG activation intervals are color-coded according to the colors used in the agglomerative hierarchical clustering dendrograms (**Figure 3**). In each row, the colored lines depict the sEMG activation intervals within a gait cycle. The sEMG activation intervals are grouped into clusters, indicated by different colors. The black lines represent the cluster centroids. Gait cycles belonging to non-representative modalities (i.e., characterized by a small number of gait cycles) are represented in the 'Modality under $Th = 10$ ' panel.

4. Discussion and Conclusions

CIMAP is an open-source and comprehensive toolbox for the assessment of muscle activation pattern from surface

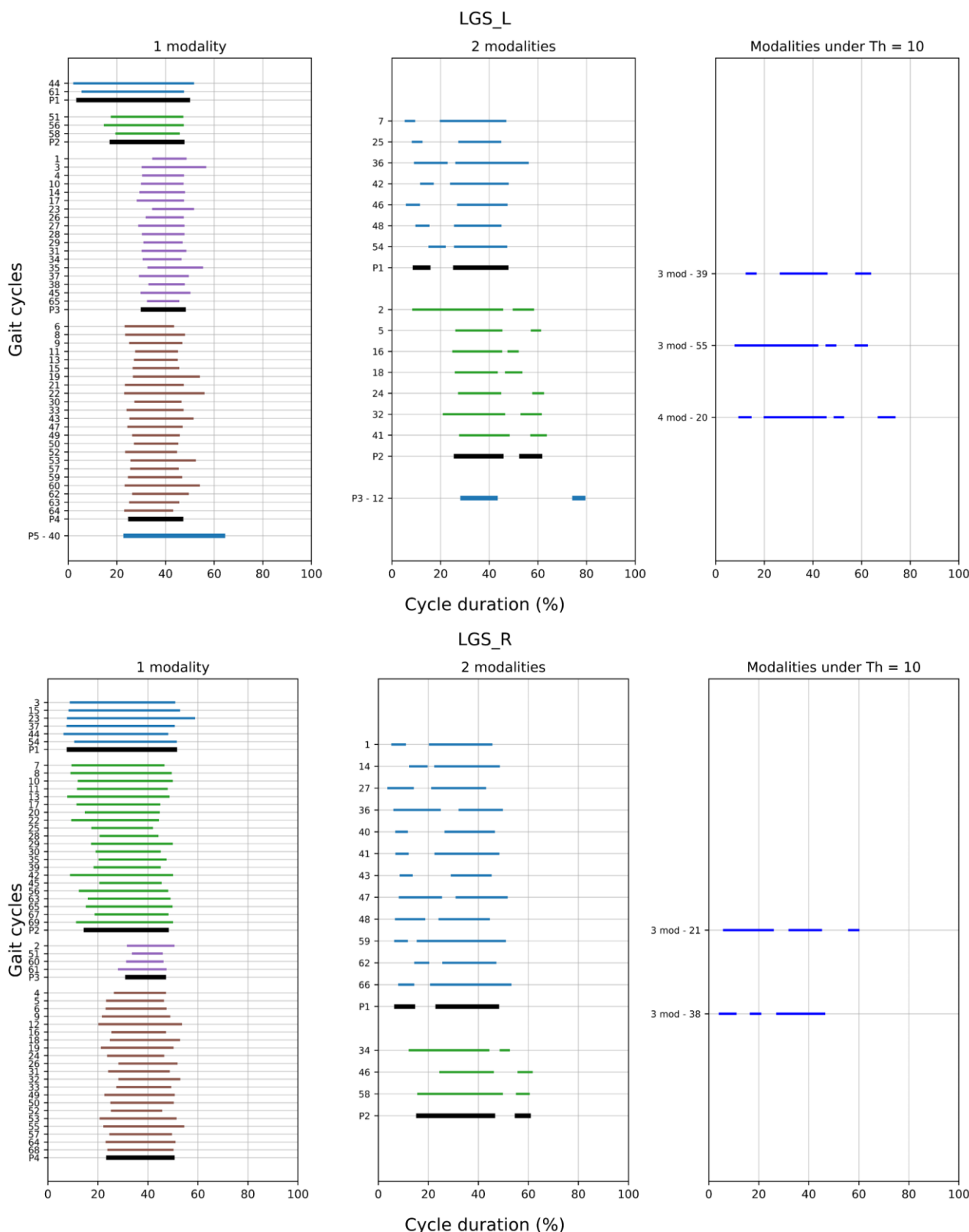


Figure 4: Example of clustering of sEMG activation intervals (muscles: left and right lateral gastrocnemius) computed by means of *CIMAP*. In each row, the colored lines represent the sEMG activation intervals within a gait cycle. SEMG activation intervals are grouped in clusters (represented by different colors) based on *CIMAP* output. Black lines represent cluster centroids. Gait cycles belonging to non-representative modalities (i.e., characterized by a small number of gait cycles) are represented in the 'Modality under Th = 10' panel.

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2
3 electromyographic (sEMG) data. The proposed toolbox offers
4 a complete analysis framework for enhancing the assessment
5 of muscle activation pattern from pre-processing of muscle
6 activation intervals to the representation of agglomerative
7 hierarchical clustering dendrograms. *CIMAP* adopts an
8 object-oriented programming approach allowing scientists of
9 any programming skill level to easily extend and customize
10 the toolbox to meet specific data and protocol needs. To better
11 explain the toolbox and offer practical guidance, an example
12 of *CIMAP* application was presented. This example involved
13 analyzing a sample dataset of sEMG signals acquired from a
14 lower-limb muscle of a healthy subject during a 5-minute
15 walk.

16
17 *CIMAP* requires as input the muscle activation intervals
18 extracted from the sEMG data of the muscles of a subject.
19 However, this toolbox does not include a muscle activation
20 interval detection step. Therefore, researchers who want to
21 analyze muscle activation patterns using *CIMAP* should first
22 apply a muscle activity detector before using this toolbox. In
23 the last years, several muscle activity detectors have been
24 proposed, spanning from approaches based on single-
25 (Hodges and Bui 1996, Solnik *et al* 2008) or double-threshold
26 (Bonato *et al* 1998) to more complex approaches based on
27 machine- (Di Nardo *et al* 2022) or deep-learning techniques
28 (Ghislieri *et al* 2021). In particular, muscle activation intervals
29 included in the sample dataset were computed using the
30 LSTM-MAD algorithm proposed by Ghislieri *et al.* (Ghislieri
31 *et al* 2021).

32
33 It is well known that muscle activations are characterized
34 by high cycle-to-cycle variability that may strongly reduce the
35 interpretability of the results. In this perspective, *CIMAP*
36 represents a first resource to be used for dealing with
37 variability in muscle activation patterns analysis during
38 cyclical movements. In the last years, *CIMAP* was validated
39 in clinics considering different kinds of disorders affecting
40 gait (such as orthopedic and neurological diseases). Even if
41 the *CIMAP* toolbox was originally developed for clinical gait
42 analysis, the clustering approach is independent from the set
43 of muscles considered, it can be easily extended to the study
44 of other cyclical movements, and it can be applied to research
45 areas different from clinics and rehabilitation (e.g.,
46 ergonomics, robotics, and sports).

47
48 From *CIMAP* outputs, several parameters can be extracted
49 to deeply understand motor control strategies during
50 movement. For example, the size and variability of each
51 representative cluster can be easily extracted to study muscle
52 activation pattern consistency of a subject muscle over the task
53 duration. During walking tasks, healthy subjects are
54 characterized by an increased cluster size (i.e., gait cycles are
55 described by the same number of muscle activation intervals
56 within the gait cycle duration) and a reduced within-cluster
57 variability (i.e., gait cycles are characterized by similar onset

and offset timings within gait cycle duration) compared to
pathological conditions. Thus, these parameters can be used to
distinguish between physiological and pathological gait
conditions.

One of the limitations of this toolbox is the absence of a
dedicated Graphical User Interface (GUI). Although a GUI
could improve accessibility, custom code may be needed to
adapt the assessment of muscle activation intervals for
different movements and datasets, which could be challenging
to implement in a GUI. However, the *CIMAP* toolbox
includes several visualization functions that enable
researchers to easily track each processing step. Another
limitation of the toolbox is the absence of a muscle activation
interval detection step. Nevertheless, the main goal of the
toolbox is to offer scientists a standardized method for
analyzing muscle activation patterns. This allows researchers
the possibility to extract muscle activation intervals based on
the specific requirements of their dataset.

In conclusion, an open-source Python toolbox for the
assessment of muscle activation intervals was presented to
help scientists to easily interpret muscle activation patterns
during cyclical movements. This approach might provide a
step forward to the understanding of motor control strategies
from muscle activation intervals in different pathological
conditions affecting movement.

5. Data availability

The latest stable release of *CIMAP* toolbox, the detailed
documentation, and a sample dataset are freely available on
GitHub (<https://github.com/Biolab-PoliTO/CIMAP>).

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CRediT authorship contribution statement

Gregorio Dotti: Data curation, Methodology, Software,
Visualization, Writing – original draft, Writing – review &
editing; **Marco Ghislieri:** Data curation, Methodology,
Software, Visualization, Writing – original draft, Writing –
review & editing; **Cristina Castagneri:** Methodology,
Writing – review & editing; **Valentina Agostini:**
Conceptualization, Methodology, Writing – review & editing;
Marco Knaflitz: Conceptualization, Writing – review &
editing; **Gabriella Balestra:** Conceptualization,
Methodology, Writing – review & editing; **Samanta Rosati:**
Conceptualization, Methodology, Writing – review & editing,
Supervision.

All the authors have read and agreed to the published
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