Interreg CENTRAL EUROPE
European Union
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niCE-life

ONLINE SLEEP MONITORING SYSTEM

System specification

Version 1
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1. Preface

Better medical care and living conditions in developed countries have increased both health and life expectancy, from approx. 50 years in the early 1900s to over 80 years now. Aging is characterized by a progressive loss of physiological integrity leading to impaired function and increased vulnerability to death. This deterioration is the primary risk factor for major human pathologies, including cancer, stroke, diabetes, various cardiovascular disorders as well as a variety of neurodegenerative diseases such as Alzheimer's disease (AD) or Parkinson's disease (PD) [1, 2]. Moreover, approximately 7% of adults over 65 years suffer from dementia and this number raises up to nearly 30% for adults over 85 years [3].

At present, dementia is an incurable disease associated with irreversible impairment and loss of cognitive abilities. The major symptoms of dementia include the progressive decline and eventual loss in cognitive skills, such as memorizing, thinking, reasoning, and speaking [4]. Alzheimer's disease is the most common neurodegenerative disorder characterized by the loss of memory and reduction in cognitive functions due to progressive deterioration of brain tissue, eventually leading to death [5]. AD accounts for approx. 60–70% of age-related dementia [6]. Currently no treatments are available to stop, slow, or reverse the progression of this disease [7], whereas symptoms of AD gradually worsen with time. In its early stages, memory loss is mild, but with late-stage AD, patients lose the ability to carry on a conversation and respond to their environment. Parkinson's disease is the second most common neurodegenerative disorder [8] associated with the progressive loss of dopaminergic neurons in substancia nigra pars compacta [9]. The primary motor symptoms of PD consist of tremor at rest, muscular rigidity, progressive bradykinesia, and postural instability [9]. Patients with PD also develop additional non-motor symptoms such as dysarthria, depression, cognitive impairment [10], etc. It has been estimated that a quarter of patients with PD have dementia [11] while 80% eventually develop dementia in the long term [12].

By 2050, there will be around 10 billion people on earth, and the population ages, the number of older people who develop any/a combination of the previously mentioned problems will also increase [13]. Currently, older adults may experience healthcare in various settings, such as hospitals, assisted living facilities, or in some cases, they can be treated at home. These situations can affect the health and function of older adults and therefore require careful management to ensure proper care and improve or maintain quality of life for as long as possible. These facts will likely result in an immense health issue with increasing economic burdens to health care systems worldwide [14]. For this purpose, various in-home remote systems for the analysis, monitoring and treatment of various age-related diseases such as PD or AD are being developed all around the world. The hope the entire world has is that in near future we will be able to develop modern tools that will enable early and precise identification of such diseases and allow us to slow down the process of neurodegeneration and improve the patient's quality of life.

Recently, rapid eye movement sleep behavior disorder (RBD) has been identified as a prodromal marker of PD [15, 16]. Moreover, it has been shown that RBD is a symptom that may precede PD by decades [17]. It is therefore getting more and more obvious that early identification of RBD will play a key role in diagnosis of PD in its early (prodromal) stages that can be crucial for the development of disease-modifying treatment as it is known that the neurodegeneration may be treated and possibly stopped before the pathological cascades even start.

Nowadays, the diagnosis and monitoring of sleep disorders and RBD in particular is conventionally performed overnight using polysomnography at a hospital/sleep clinic. Although polysomnography is the gold standard for sleep quality assessment, it can be invasive, disruptive to sleep as well as expensive. For this purpose, other approaches have been extensively investigated. One such approach is the use of actigraphy. The actigraphy is much more comfortable than polysomnography, the price of an actigraph is approximately EUR 300, and it can be used repeatedly while requiring battery exchange after several years. In addition to that, it is not bound to a patient's presence at a sleep clinic and therefore allows for in-home sleep assessment and monitoring. Hence it is no surprise that there are various applications for an online sleep monitoring tool such as the assessment of exploding head syndrome, sleep terror, narcolepsy, idiopathic hypersomnia, etc.

With the previously mentioned information, the online sleep monitoring system that will be developed in the frame of the niCE-life project will focus on the assessment and monitoring of sleep in relation with RBD. Using actigraphy, digital signal processing techniques, state-of-the-art machine learning and statistical modeling algorithms, it will provide a client-server web application that enables for remote assessment and monitoring of sleep disorders. The system is not limited to a specific country as PD is the most common neurodegenerative condition after AD affecting an estimated 1.2 million people in Europe alone with the incidence of PD being forecasted to double by 2050 primarily as a result of the aging population. Therefore, an actigraphy-based sleep monitoring tool has a high potential to be used in the entire EU, to make the acquisition, analysis, assessment, and monitoring of sleep data more accessible and easier to deploy aiming at day-to-day use in clinical practice.

2. System description

The online sleep monitoring system will offer an intelligent software (SW) solution, providing advanced data-oriented services to health and care centers and communities to support virtualization of medical care and data-driven approach to medical centers (i.e. advanced data/driven analytics). It will imply secured data transfer and storage for uploaded data from medical centers, care centers, or patients' homes (the data will be uploaded from actigraphs) and state-of-the-art artificial intelligence algorithms (allowing execution of sophisticated data and also providing useful feedback as a result of analytics.

The system will be scaled based on different accounts (for patients, doctors, administrators). It will enable users to make data parametrization (i.e. descriptive characteristics of sleep), automatic processing (e.g. identification of sleep stages based on machine learning modelling), visualization, and statistical analysis. The system will have a web-based interface that will enable users to securely access the application from various common device (e.g. laptops, tablets, smartphones) connected to the internet. The concept will be in line with the GDPR.

The system will enable comfortable sleep data acquisition (in comparison to the polysomnography) that can be performed at a patient's home (such a system is not bound to a patient's presence at a sleep clinic). Next, it will allow for performing various complex and advanced (when utilizing state-of-the-art machine learning approaches) diagnosis, assessment and monitoring of sleep disorders that are associated with many age-related diseases, e.g. with Parkinson's disease.

3. Use-case definition

The proposed system will be designed to enable easy, in-home sleep quality measurement, assessment, and monitoring using affordable wearables and modern technologies. From the high-level perspective, the workflow (use case) can be described as follows:

1. A patient at risk of having/developing sleep disorders (as mentioned in the previous section, this can be a prodromal market of developing a neurodegenerative disorder such as PD) borrows an actigraph from a doctor.
2. Next, he/she wears it for a couple of days during sleep according to the instructions provided by the doctor to acquire large enough data sample to be analyzed by the sleep monitoring system.
3. Then, he/she uploads the sleep data via the web interface/or brings the actigraph to the doctor for the processing. And finally, he/she gets a detailed report about his/her sleep from the doctor.

This simplified use case scenario can be seen in Figure 1 (1-2: data acquisition. 3: data storage, processing and analytics, 4: sleep report combining the output of the sleep monitoring system and the doctor's expertise in the given field).

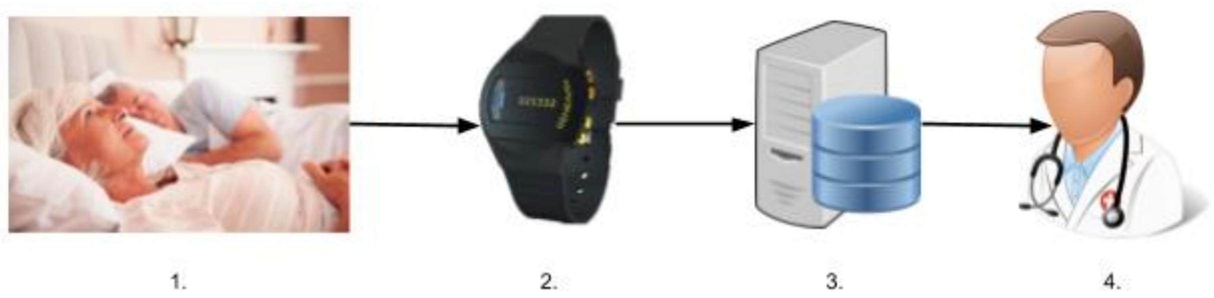

Figure 1: Use-case scenario: sleep data acquisition, processing, and assessment.

From the technical perspective, there can be multiple roles involved in the data acquisition, uploading of the data into the system, data management, output presentation, etc. Most of these roles can be performed by a doctor or an administrator (will be described below), however, before the deployment of the model, there are phases that could benefit from splitting the responsibilities into multiple roles (i.e. when the system is to be used, the machine learning models have to be trained, for this purposes, data collection, tagging, processing, etc. need to be finished, etc.): a) researcher, b) technician, c) coordinator. The responsibility assignment matrix used in the proposed system can be seen in Table 1.

Table 1: Responsibility assignment matrix.

	subject	researcher	technician	coordinator
Actigraph configuration	I	R		A
Data acquisition	R	A		
Control visit	R	A		I
Data downloading	I	R		
Data preprocessing		R	A	A
Data upload to the system		R	A	
Server configuration		I	R	A
User-accounts management		I	R	A
Data tagging			I	R
Machine learning model definition			I	R
Machine learning model training			R	A
Machine learning model application			R	I
Results interpretation		I	R	R
Results publication	I	I	R	A

After the system is deployed (in the real clinical use), there can be another role besides a patient and a doctor, and that is the administrator. This is a person who is responsible for management of the system, e.g. creating/editing/removing of doctor accounts or patient accounts. The use case scenario is described in more details in the next sub-sections.

3.1. Use case: doctor

A doctor will provide a patient with an actigraph and some instructions regarding wearing it. The patient will wear the actigraph during sleep. After some certain number of days (depending on the kind of analysis) the patient will upload the data from the actigraph via the online web interface, or he/she will send/bring the actigraph back to the doctor (who will upload it on the behalf of him/her). The doctor will be able to create a patient's profile in the system and to manage/edit this profile. The profile can be shared among several doctors. After the data are uploaded, the doctor can visualize them, compare (e.g. among several days or patients), parametrize (extract sleep measures), and apply the trained machine learning models (e.g. to detect sleep stages, specific sleep disorders, etc.). The system will also enable to export the data into commonly used formats.

3.2. Use-case: patient

A patient wears a borrowed actigraph during sleep according to the instructions given by a doctor to collect sleep data for the consequent processing and analysis. After the data is collected, a patient will be able to upload the data into the system via his/her profile. If allowed by a doctor (who will manage the rights along with an administrator (for more information, see below)), he/she can see a part of or the results of the analysis.

3.3. Use-case: administrator

An administrator will have the same rights as the doctor or the patient. In addition, he/she will be able to create/manage profiles of doctors/patients. He/she will be able to manage the user interface, processing pipelines, etc. In this regard, an administrator will take care of the system in terms of its functionality, security, management, etc. so that a doctor can focus on the medical tasks taking an advantage of the system without additional burden related to the system's operation.

4. System design

The online sleep monitoring system will be designed as a client-server web application. The frontend part of the system serves for the presentation of the results to a patient (and other people involved in the operations) as well as a gate into the system itself (used by all parties involved, e.g. patient(s). doctor(s) as well as administrator(s)). The backend part of the system serves for data storage, data processing, data analysis, data/user/access/rights, etc. management, results generation, communication with the frontend part, etc. It provides a computational power to the analysis and uses the frontend part to interact with the end-users. As mentioned in the section 3 (use case(s)), there are multiple steps from the perspective of the system's technical architecture and design such as data acquisition, data processing, machine learning (sleep prediction), etc., that will be described in the next few sub-sections.

4.1. Data acquisition

ActiGraph is a device dedicated to providing end-users with highly accurate, innovative, cost effective and objective monitoring solutions for sleep monitoring (among other capabilities). There are many manufacturers on the market offering various actigraphs that differ in many sleep monitoring-related characteristics such as the internal memory, battery capacity, the presence of an accelerometer, etc.

During the system's designed, the following actigraphs were compared among each other in order to use the most suitable one given its characteristics and price (characteristics and overview of the compared commercially available devices for sleep monitoring can be seen in Table 2):

1. Mbientlab 9-axis IMU [18].
2. Actigraph wGT3X-BT [19].
3. Activinsights GENEActiv [20].
4. Philips Respironics Actiwatch Pro [21].
5. Fitbit Charge 3 [22].
6. Mobvoi Tiewatch E [23].
7. Misfit Vapor [24].
8. Garmin Vivoactive3 [25].
9. Samsung Fit2 Pro [26].

Table 2: Overview of the commercially available devices for sleep monitoring.

	Actigraph model name	Battery capacity	Memory capacity	Presence of accelerometer	Presence of thermometer
Mbientlab	9-axis IMU	7 days	8 Mb	Yes	No
ActiGraph	wGT3X-BT	25 days	4 Gb	Yes	Yes
Activinsights	GENEActiv	45 days	4 Gb	Yes	No
Philips Respironics	Actiwatch Pro	60 days	32 Mb	Yes	No
Fitbit	Charge 3	7 days	Unknown	No	Yes
Mobvoi	Tiewatch E	2 days	4 Gb	Yes	Yes
Misfit	Vapor	2 days	4 Gb	Yes	Yes
Garmin	Vivoactive3	7 days	Unknown	Yes	Yes
Samsung	Fit2 Pro	3 days	4 Gb	Yes	Yes

After the comparison, the lightweight, waterproof, wrist-worn actigraph GENEActiv from Activinsights [20] was chosen for the sleep data acquisition in the monitoring system. Among other benefits, it provides open source analytics and open SDKs, it is ergonomic, and it has aesthetically neutral design with maximum subject acceptance and wear compliance, which is also important especially for elderly people. The GENEActiv actigraph can be seen in Figure 2.

Figure 2: GENEActiv actigraph device [20].

This actigraph provides raw data output including acceleration in 3 axes, physical activity intensity, sleep/wake measurements, etc. The acquired data is stored in the internal memory and can be easily accessed and downloaded via the *GENEActivPcSoftware* application available for the Windows operating system. The raw data provided by the actigraph are the following:

- acceleration in x-axis [g], range: (-8, 8), resolution: 0.0039 g
- acceleration in y-axis [g], range: (-8, 8), resolution: 0.0039 g
- acceleration in z-axis [g], range: (-8, 8), resolution: 0.0039 g
- light level [lux], range: (0, 5000), resolution: 5 lux
- state [on/off]
- temperature [°C], range: (0, 70), resolution: 0.1 °C

The raw data series are stored in *.bin format (as a column delimited data) during the acquisition. Each row contains the previously mentioned information (row index, timestamp, acceleration in x, y, z axes, etc.) An example (9 randomly selected rows):

```
1 2013-06-11 02:50:58:505, 0.9573, 0.2857, 0.0989, 0, 0, 31.4
2 2013-06-11 02:50:58:516, 0.9573, 0.2779, 0.1067, 0, 0, 31.4
3 2013-06-11 02:50:58:528, 0.9612, 0.2741, 0.1107, 0, 0, 31.4
4 2013-06-11 02:50:58:540, 0.9651, 0.2974, 0.1185, 0, 0, 31.4
5 2013-06-11 02:50:58:551, 0.9495, 0.2779, 0.1107, 0, 0, 31.4
6 2013-06-11 02:50:58:563, 0.9495, 0.2702, 0.1224, 0, 0, 31.4
7 2013-06-11 02:50:58:575, 0.9534, 0.2779, 0.1028, 0, 0, 31.4
8 2013-06-11 02:50:58:586, 0.9690, 0.2702, 0.1028, 0, 0, 31.4
9 2013-06-11 02:50:58:598, 0.9534, 0.2935, 0.1302, 0, 0, 31.4
```

The raw data can be converted from *.bin format into a tabular for as *.csv that is easily accessible via common tabular data processors. The system also expects the data to be downloaded from an actigraph and uploaded as a *.csv-formatted data for further processing.

4.2. Data processing

Data processing involves the following steps: a) data cleaning, b) data pre-processing, and c) data processing. As stated above, data are gathered in the form of a time series stored in a *.bin format that is converted into a *.csv format. Data cleaning involves handling of missing values, corrupted values, etc. using the commonly used techniques in data science such as data imputation (median), etc. Next, data pre-processing involves conversion of data units, and the data transformation (if necessary). Finally, data processing involves the selection of only sleep duration estimation-relevant data, i.e. acceleration in x, y, and z -axes, temperature, and the timestamp, and data-subsampling (from 85 Hz into one third; this is in line with the previous studies dealing with machine learning using actigraphy).

4.3. Data analysis

The accelerometer information (x, y, and z -axes) and the temperature are next used for the consequent data parametrization (extraction of relevant parameters that describe the information in a way that is not visible from its raw form). Each data vector (or series; i.e. information (x, y, and z -axes) and the temperature) is segmented using 30s floating window to create a matrix of data segments. Each of the segments is then parametrized and handled individually. The parametrization involves computation of 45 statistical functionals that describe the statistical properties of the given time series data. The following statistical functionals are used:

- min, max, relative position of min., relative position of max.
- range, relative range, relative variation range, interquartile range, relative interquartile range, interdecile range, relative interdecile range, interpercentile range, relative interpercentile range, Studentized range
- mean, means excluding 10/20/30/40/50 % of outliers, median, mode
- variance, standard deviation, median absolute deviation, relative standard deviation, index of dispersion
- kurtosis, skewness, Pearson's 1st skewness coefficient, Pearson's 2nd skewness coefficient
- 1st/5th/10th/20th/25th/30th/40th/60th/70th/75th/80th/90th/95th/99th percentiles

In total there are 45 parameters for each segment, and this is computed for every time series that was mentioned, i.e. the matrix of parameters (also called feature matrix in machine learning) then contains all parameters (features) used for consequent sleep-related predictions.

4.4. Sleep prediction

Next, each parameterized 30s timeframe (feature matrix) is put into a pre-trained binary classification model that predicts if a subject is sleeping at that moment in time or not. After this step, the system has a time series of sleep predictions. To avoid misclassification, the system applies further logic that for instance takes care of rare, short-time misclassifications of a person being awake while sleeping, etc.

The prediction is made by a state-of-the art machine learning algorithm, belonging into the so-called gradient boosting framework, named XGBoost [27]. XGBoost provides an extreme parallel tree boosting that solve many data science problems in a fast and accurate way and is currently on of few algorithms capable of competing with deep neural networks (deep neural networks however need to be trained on huge datasets, which is still not suitable for medical application because they work with small datasets most of the time). XGBoost is also robust against outliers, it can handle missing (censored data), it provides feature importance computation (feature ranking; some features are expected to be more important that others and capturing such importance is likely to bring clinical relevance to the predictions), and it is also optimized to run on both CPUs as well as GPUs.

5. System implementation

5.1. Hardware

5.1.1. Server-side

From the perspective of server-side hardware, the system is developed on a consumer-level notebook, specifically: Acer Aspire V15 Nitro Black edition. Therefore, a server that is to be used in the real use should satisfy at least the following hardware/computational requirements (as can be seen, unless a very high demand is expected, a consumer-side hardware is capable of running the server-side of the sleep monitoring system with no issues):

- CPU - Intel Core i7 4710HQ, 4 × 3, 5 GHz
- GPU - NVIDIA GeForce GTX 860M, 2GB
- RAM - DDR3, 16GB

It is also recommended that SSD (128GB), and HDD (1000 GB) is used to mimic the development environment, however, this is not crucial as the previous parameters, and it can change as long as the data storage is not going to become a bottleneck.

5.1.2. Client-side

From the perspective of client-size hardware, the system is not challenging to be deployed in real day-to-day use. The data acquisition part in terms of downloading data from the actigraph can be managed at any consumer-level computer running on the Windows operating system supporting the *GENEActivPCSoftware* application. Next, the data can be easily uploaded to the server using any device with a standard internet browser and the internet connection (PC, notebook, tablet, etc.).

5.2. Software

5.2.1. Server-side

Server-side is the key part of the entire system. It takes care of the data storage, data processing, data analysis, presentation of the results, user management, etc. It is developed using a Linux-based operating system (Fedora) running in a virtual environment set-up on the Windows 10 operating machine. The reasons for virtualization comprise security, easy migration, etc.

The entire server side is programmed in Python programming language (v. 3.7 stable [28]), and Django (an open-source web application framework [29]) framework that supports a modern approach to web development, namely the MVC (model view controller) model. One of the reasons to choose Python is its dominance in data science applications, especially machine learning and artificial intelligence in general.

Data are stored in the SQLite database [30], which is natively supported by the Django framework. To make the system modular, the database is accessed via a database access layer. Among other data such as users, subjects, etc., the database holds paths to individual actigraph-data stored in *.csv file(s). The server-side of the system is deployed using NGINX server [31].

The system can be divided into the three logical pieces:

- Homepage
- Dashboard
- Administration

5.2.1.1. Homepage

The homepage presents the system itself; it shows basic information about the system (how it works, what it provides, etc.), and holds links to other parts of the system. The design of the system's homepage can be seen in Figure 3.

5.2.1.2. Dashboard

The dashboard is used to present the analytical results about the sleep of the individual subjects. Dashboard data cannot be edited, they are to be viewed only. First, the dashboard presents the list of all subjects, where each subject has his/her own unique identifier. This site is publicly available. After a subject is selected, more information is shown. The list of subjects can be seen in Figure 4, and a subject's detail can be seen in Figure 5.

5.2.1.3. Administration

The administration page is used to add/edit/remove subjects, manage their rights and data, etc. A design of an administration dashboard can be seen in Figure 6 (it can be seen that a super-user has rights to manipulate also with the machine learning part of the system).

5.2.2. Client-side

From the client-side of the system, the system requirements are the following:

1. A person responsible for data uploading (researcher, technician, doctor) needs a PC compatible with *GENEActivPcSoftware* (so that it is possible to upload data from the actigraph into the system itself). The PC should have USB connector(s) and run on Windows 7 and higher. Next, a standard web browser capable of rendering HTML 5 content is needed.
2. A subject only needs a consumer-level device such as PC, notebook, tablet or even smartphone (the system's website is developed to use the responsive design to maximize the user experience that is especially helpful for elderly people that may not be used to modern technologies on the web) and a standard web browser capable of rendering HTML 5 content to access the system's website.

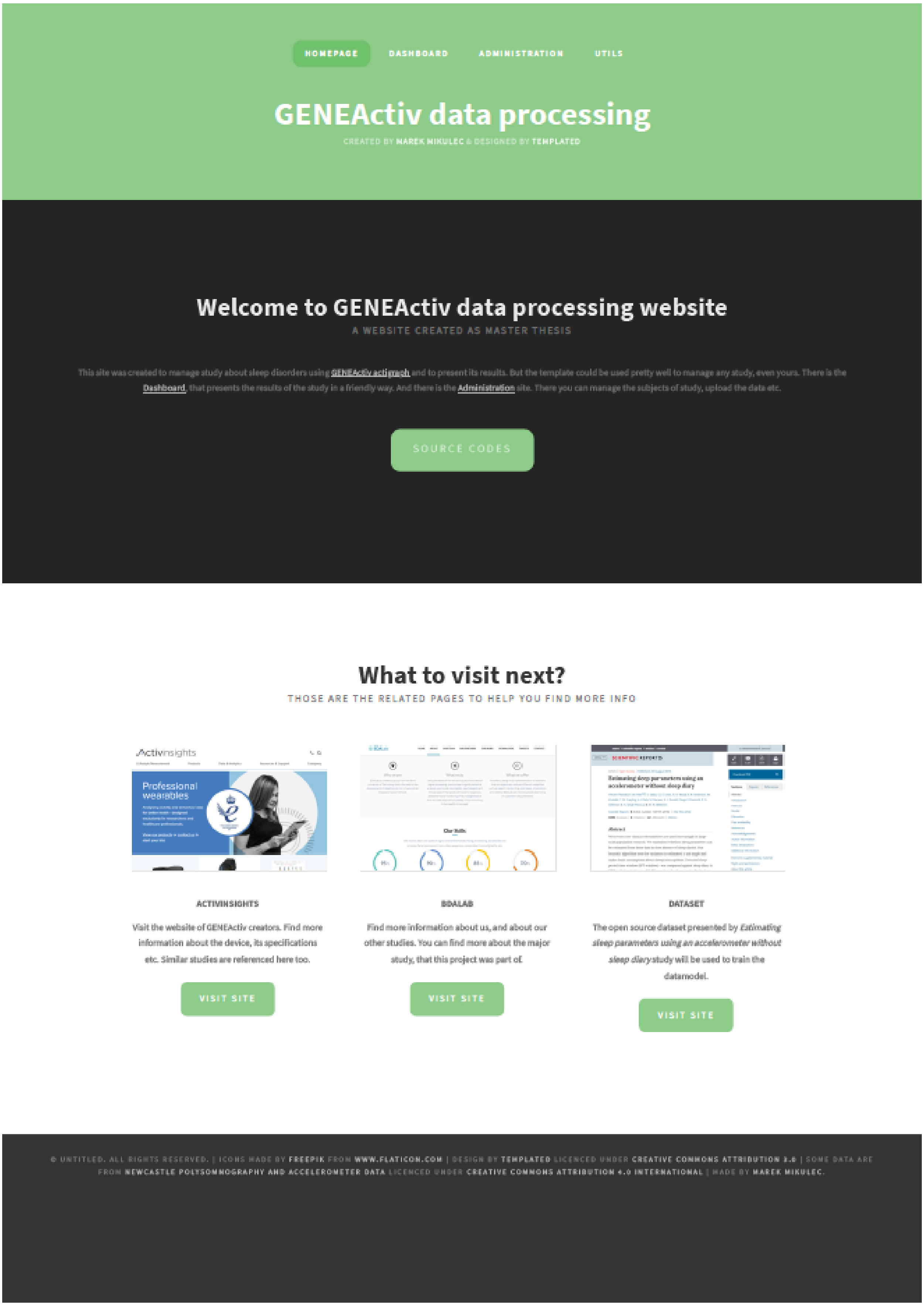

Figure 3: Design of the homepage.

Figure 4: Dashboard: a list of subjects.

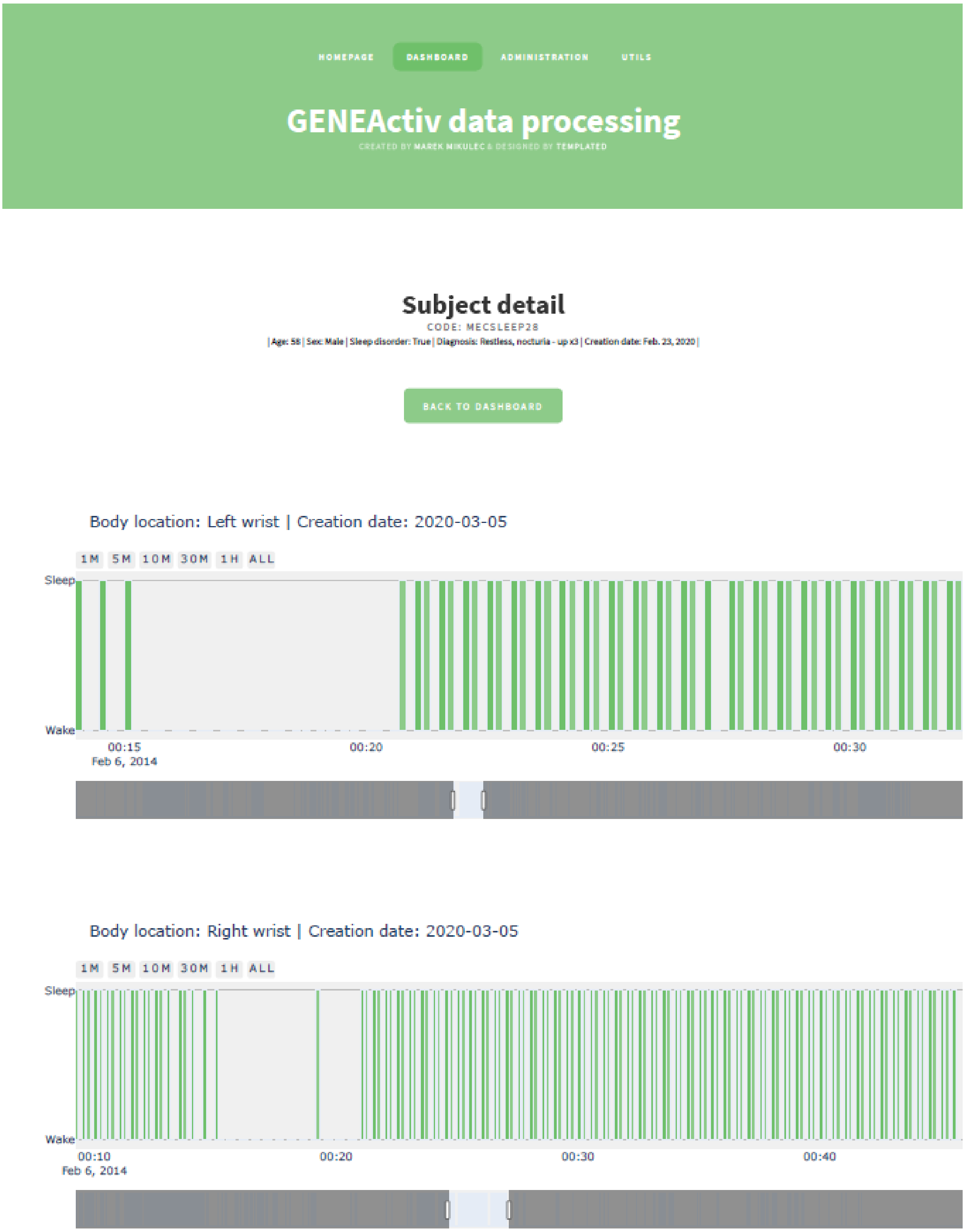

Figure 5: Dashboard: a subject's details.

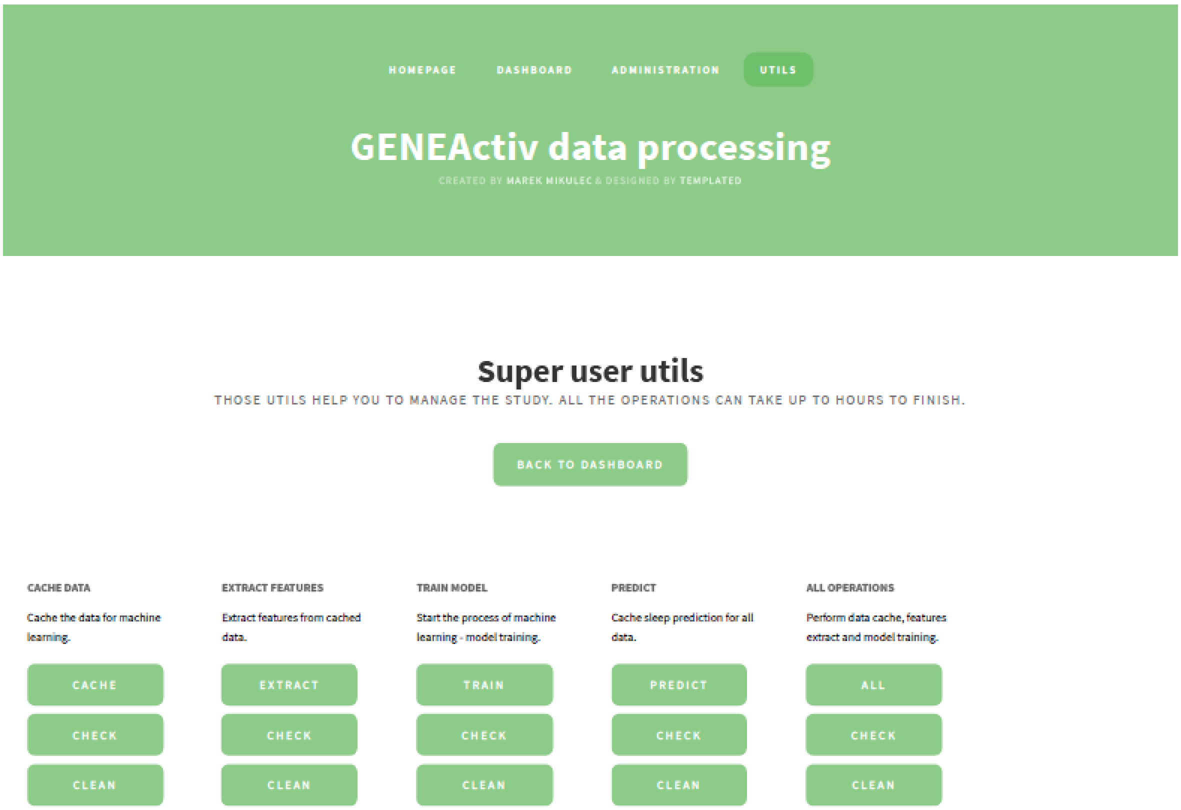

Figure 6: Administrator dashboard.

5.2.3. Security

To ensure the maximum possible security, the server-side of the system holds a database of user accounts. To authenticate, a user-password combination is required. To make the authentication as secure as possible, various password policies are applied (to see an example of an example password policy in action, see Figure 7). These password policies can be changed if needed (to make the authentication less/more strict).

After successful authentication, a session ID is generated, and cookies is stored in the web browser so that it is unnecessary to authenticate every operation after the successful login. This step is fully supported and built in the Django framework itself. The password is stored in the form of SHA-256 hash. A password has to satisfy a pre*defined list of security criteria for the maximum security (an administrator can change the list for increase the strictness if needed).

Moreover, to distribute the rights accordingly, a set of user groups is defined:

- Administrator(s)
- Researchers(s) or technician(s)
- Subjects(s)

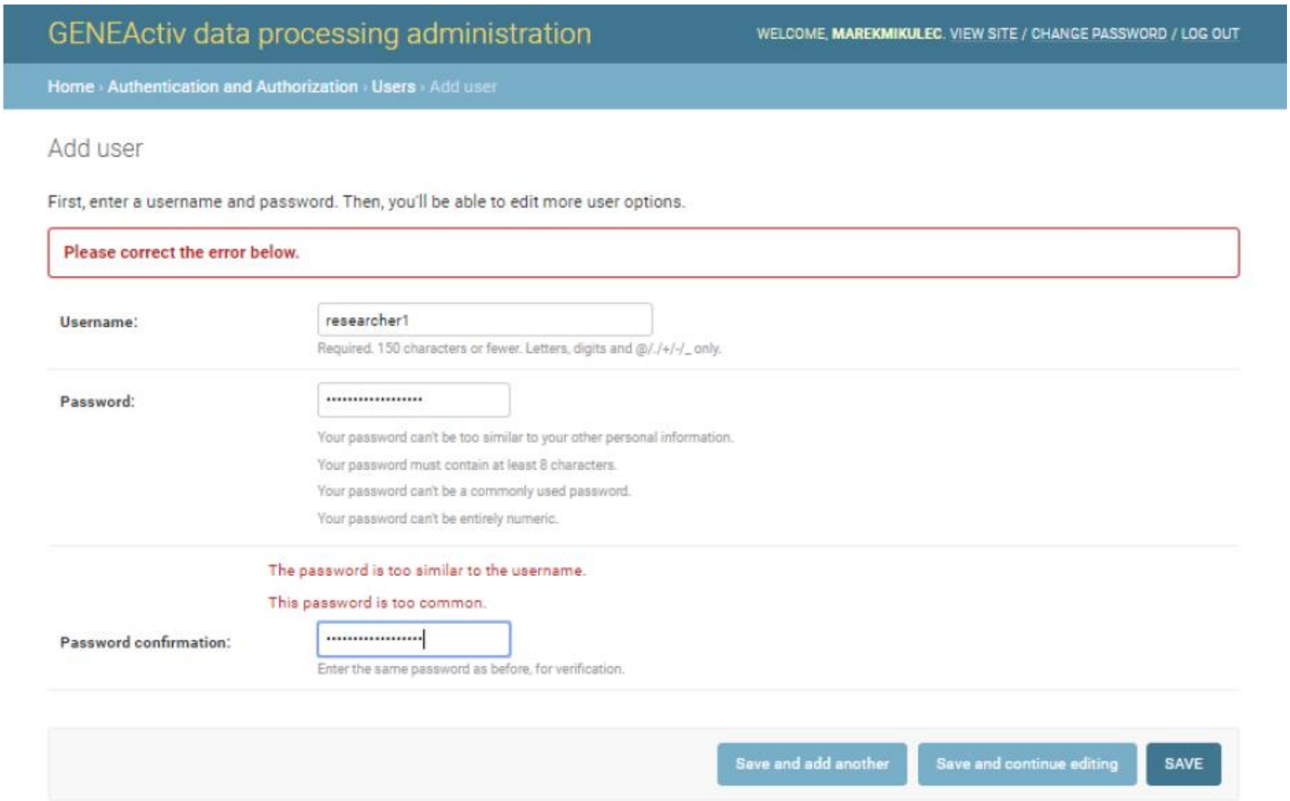

Figure 7: Password policies.

5.2.3.1. Administrators

Administrators are represented by the study coordinator and server administrator(s). Everyone in this group has the full rights to manipulate with users and data (create, edit, delete, etc.). An administration dashboard (a super-user dashboard) can be seen in Figure 6.

5.2.3.2. Researchers

Researcher(s) or technician(s) are responsible for uploading subjects' data into the system and communicate with the subjects. For this reason, they have the rights to edit subjects and their data. they however don't have the rights to edit user accounts and rights (only available to administrator(s)). The also cannot see the results of an analysis of a subject.

5.2.3.3. Subjects

The last group, represented by the subjects themselves, after using their ID and password can access the results of the analysis for their own data in the system's dashboard. They have no other rights; they cannot see others results as well as cannot alter any of the data anyhow.

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