A software system for the assessment of the sleep-wake rhythm using Axivity AX3

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Abstract—Mobility limitations are a major public health concern along with physical inactivity because they limit an individual's independent life, and, worse, have shown to be key risk factor for several morbidity, including cardiovascular. It is important to investigate modifiable factors that might help preserve mobility, especially in later life. In this work we present the development of the software system Axivity, that supports specialists in conducting in-depth research on patient activity, taking into account data recorded by an actigraph (a simple and non-invasive device used to diagnose sleep) and data provided by the patient or care provider, so as to provide also relationships between activity energy expenditure estimated from wrist-worn accelerometers and the intensity of physical activity. It will be shared as open source.

Index Terms—Physical activity, Mobility limitations, noninvasive system, IoT, cardiovascular disease, Sleep duration

I. Introduction

A sedentary lifestyle is a risk factor for cardiovascular disease, diabetes and cancer, so regular physical activity is one of the most important elements in maintaining good health. According to the World Health Organization, physical activity means: "any effort exerted by the musculoskeletal system which results in a consumption of energy higher than that in conditions of rest". This definition therefore also includes simple daily movements such as walking, cycling, dancing, playing, gardening and housework. With the practice of regular physical activity, the heart becomes more robust and resistant to fatigue. Aerobic activity increases the body's oxygen demand and the workload of the heart and lungs, making circulation more efficient. A trained heart pumps more blood without additional energy expenditure. Exercise regularly and moderately:

- helps you lose weight;
- improves blood pressure;
- burns fat and improves blood cholesterol;
- helps prevent and control diabetes;
- it is an excellent stress reliever;
- decreases the desire to smoke;
- it is a good way to socialize.

To get to 30 minutes of moderate physical activity a day, even simple activities are enough, such as walking or cycling to work, taking the stairs instead of using the elevator, doing housework.

A device used to record human movements during the waking phase, therefore also during physical activity is the actigraph. The dimensions of the actigraphs are comparable to those of wrist watches, and wearing them is not very invasive for the subject. The fields of application of similar devices are numerous [1]. Historically, one of the first applications has been in the sleep clinic, in which actigraphs are used to evaluate circadian sleep-wake rhythms and their disturbances. Physical activity serves to improve the sleep-wake rhythm, thanks to the release of endorphins and to ensure greater oxygenation of the tissues. A study by the University of Stanford (USA) conducted on insomniac subjects between the ages of 50 and 76 showed that, undergoing a 3-hour weekly training program, highlighting signs of improvement in sleep quality [2] [3] [4] [5] [6]. An article published by the World Health Organization (WHO) states that adults over the age of 65 should do at least 150 minutes of physical activity with moderate intensity or 75 minutes with high intensity. This not only leads to improvements in the quality of sleep but also in the cardio-respiration and mental health of the patient as it keeps the patient active and prevents them from falling into depression or disabling diseases [7] [8] [9] [10]. According to a study carried out [11], the level of physical activity also depends a lot on the environment around us, in fact those who live near green areas such as parks or in rural areas perform more physical activity than those who live in areas with more pollution [12].

A simple method for assessing the intensity of physical activity is the Metabolik Equivalent Task (MET). The MET expresses the expenditure of oxygen during an activity and is equivalent to a consumption of 3.5 ml of oxygen per kg of body weight per minute. Therefore, the number of MET indicates how many times the effort of a certain physical activity is greater than in the state of rest: it is therefore an estimate and not a real measurement, so that in reality there may also be variations in the actual energy consumption between people who carry out the same activity, as it depends also on age, gender and physical fitness. A study on METs is detailed in the article [13]. Factors such as age, weight and not smoking affect the amount of physical activity performed, as demonstrated in [14] [15], where older people, smokers and overweight people generally showed a low level of motor activity. A new important impetus on the subject of the evaluation of physical activity carried out derives from the effects of the recent pandemic on human lifestyle. Daily life was profoundly influenced by factors such as reduced physical activity, reduced light exposure, worsening sleep quality and altered sleep-wake rhythm. Furthermore, the pandemic has negatively affected people's mental wellbeing, leading to high levels of anxiety and stress. Reducing physical activity carries multiple health risks, such as high blood pressure and low density of lipoprotein cholesterol. The thought of the loss of work and the closure of many activities also led to a very high level of stress and anxiety leading to a worsening of the quality of sleep or even insomnia. A very interesting article dealing with this topic is [16].

II. The study of sleep

Getting enough sleep is essential for the quality of our life. Sleep is more than a moment of rest for body and mind, in fact the body works to rebuild the tired muscles during the day and eliminates the waste that is produced in the brain. These life processes are meant to keep the body and mind functioning well, being sleep also essential to regulate emotions: in fact, not sleeping even for a single night can increase the response to negative feelings by 60% [17]. Lack of sleep makes it difficult for the body to regulate essential functions such as appetite control, the immune system, good metabolic function, and the ability to maintain a normal body weight. Sleep plays an important role in regulating the circadian rhythm, the biological clock, and can also help regulate metabolism, immune response and inflammation. The hormone that regulates the maintenance of the sleep-wake rhythm is melatonin: its integration can prove to be very effective in subjects with alterations of the biological clock. Those who do not sleep well or do not have good sleep quality often end up seeking medical attention. The first step in medicine is sleep monitoring [18] [19] [20] [21] and define a clinical pathway [22].

There are two methods to monitor sleep quality, polysomnography and actigraphy. Polysomnography is a diagnostic test that must be performed in a specialized facility. It consists of applying a series of sensors to the patient's body and measuring a large amount of data during sleep. The parameters measured are: brain activity (electroencephalogram, EEG), eye movement (electrooculogram), breathing and body movements (electromyography), blood oxygen saturation (pulse oximeter). Although polysomnography is a complete and very accurate examination, it cannot be repeated for several days because the patient would be forced to sleep several consecutive days in the clinic. Sleeping outside the home, and moreover with all these sensors attached to the body, in itself could be even an additional sleep disturbance.

Actigraphy is a much simpler and less invasive examination than polysomnography. It consists of applying a special tool called an actigraph to the patient's wrist before he falls asleep. The actigraph records the actions and movements of the wrist to which it is applied, by means of motion sensors, similar to those integrated in smartphones, which monitor how much the patient moves during the night. From the movements that are recorded it is possible to understand, in general, the sleep-wake rhythm and the number of awakenings of the patient during the night. It is easy to understand that this methodology is less precise than polysomnography, but it can provide important preliminary information on suspected diagnostics, and has the great advantage of being done at the patient's home. Studies have been carried out on the efficiency of actigraphs with good results [23] [24] [25] [26] [27] [28] [29]. The registration period usually lasts one week, but can range from a minimum of one day to 14 days. During this period the patient is asked to write down his main daily actions in a diary in order to easily discover false positives in the detections of the actigraph. By false positives we mean those occasions when, based on the data obtained from the device, periods of low activity are confused with periods of sleep.

The software that accompanies the actigraph devices are generally useful for displaying raw or graphical data limited to a single type of analysis and a single patient. To increase the effectiveness of the study of a patient's activity, mobility and sleep disorders, it is instead necessary to relate numerous other factors, such as nutrition, cognitive problems, memory problems, environmental etc. It is therefore necessary to have more advanced software available that allow to extract raw data from devices, offer the possibility of recording other factors and characteristics of the patient, in order to monitor the patient and his data in a broader way, also with reference to the time. Taking note of patient's main daily actions in a electronic diary is also welcome.

In this work we present the development of the software system Axivity that supports specialists in conducting in-depth research on patient activity, taking into account data recorded by an actigraph and data provided by the patient or care provider, so as to provide also relationships between activity energy expenditure estimated from wrist-worn accelerometers and the intensity of physical activity.

III. The Axivity AX3 device

The device used in this study is Axivity AX3. This actigraph consists of:

- a triaxial accelerometer (configurable to ± 2/4/8/16 g);
- a light sensor (range 3-1000 LUX);
- a thermometer (range 0 - 40 °C);
- a quartz clock to indicate the real time;
- an RGB LED to indicate the status of the device;
- a non-volatile 512 MB NAND memory;
- a microprocessor;
- a rechargeable lithium polymer battery.

The accelerometer has configurable sample rates, adjustable sensitivity, and a low-power mode. High sampling rates reduce battery life but is designed to sample at a rate of 100Hz for at least two weeks on a full charge. The low-power mode reduces power consumption and increases battery life but introduces noise, which is detrimental to the accuracy of the recording. The accelerometer has variable sensitivity to allow it to be used in many applications. The selectable ranges are ± 2, 4, 6, 8 g (acceleration of gravity).

AX3 has a built-in NAND Flash memory chip to record accelerometer data. The internal memory is used to store the raw binary data from the sensors; data compression, error detection and correction are performed by firmware. Sensors allow to record data continuously up to a maximum of 21 days, while charging time is approximately 90 minutes. The device is suitable for use in a variety of environments, even underwater with a maximum depth of 1.5 meters [30] [31].

IV. Axivity Software

The software we developed for the analysis of patient's activity was written in Python using in particular the PyQt5 library as regards the implementation of the graphical interface, and the numpy and matplotlib for the realization of the graphs. Our Axivity software allows the operator to enter his own data and create a personal folder in which files will be created concerning all monitored patients. For each patient, by interacting with the OmGui libraries (open source belonging to the Open Movement project), it is possible to set up and configure the AX3 device for recording, download and view the data recorded by the device. From the data flow obtained from the device it is therefore possible to obtain and analyze:

- the number of awakening;
- the hours of sleep;
- the average physical activity level in mg;
- the lifestyle held by the patient during the registration period;
- the total time the patient has not worn the device;
- minutes of physical activity carried out with light intensity;
- minutes of physical activity performed with medium intensity;
- minutes of physical activity performed with high intensity.

The values of the first five parameters are also reported based on the various time frames of the day (morning, afternoon, evening, night). The algorithms taken into consideration to estimate the indicators useful for monitoring the patient's activity are described now.

A. Signal Vector Magnitude (SVM - gravity-subtracted)

Accelerometers are portable devices which categorise the physical activity level base on the Signal Vector Magnitude (SVM) in three different Axis (vertical(Y), horizontal rightleft (X) and horizontal front-back axis (Z)). There are studies in literature which used the accelerometers for the objective measurement of physical activity [32] [33] [34] in adolescents during shuttle run test. To date there is no evidence to evaluate accuracy of the wrist worn Axivity algorithms using the (SVM) during a vigorous activity, but as here we are dealing with normal daily activity, this cannot be considered a limitation. Signal Vector Magnitude has proven to be a useful measurement quantity when specific axis information is not required. The fundamental characteristics for the calculation of the SVM value are:

- Epochs: period of time in which the average value of SVM is calculated. The default is 60 seconds, if the number of samples in the file does not fall within an exact number of epochs, the last epoch will be partial.
- Mode: The SVM calculation used in this study is of the type $|\sqrt{(x^2+y^2+z^2)}-1|$. Basically, the Euclidean norm of the values obtained from the 3 axes of the accelerometer is calculated and then 1g is subtracted, due to the force of gravity when stationary.

B. Cut-points

When using accelerometers to measure physical activity it is helpful to calculate the time spent in a certain state. The analysis of the Cut-points reports the time taken to carry out an activity at a specific level of intensity. Each intensity level is classified according to units of the Metabolic Equivalent of Task (METS). The algorithm used to create this file considers the average SVM value calculated in one minute and based on that an activity level is assigned: sedentary (< 1.5 METS), light (≥ 1.5 METS, < 4 METS), moderate (≥ 4 METS, < 7 METS) and vigorous / high (≥ 7 METS).

C. Wear Time Validation (WTV)

The Wear Time Validation algorithm was designed to have a vision of when the device was worn or not. The time is estimated from the standard deviation and the range of values of each axis of the accelerometer calculated over periods of 30 minutes. Each period is classified as a non-wearable period if the standard deviation is less than 3.0mg from at least two of the three axes, or if the range of values for at least two of the three axes was less than 50mg. The results are summed if multiple 30-minute intervals are chosen. The units considered are the sum of the number of 30-minute windows detected within the period. For example, if the period is one hour and the device is worn for the duration of the period, the result will be 2. If it is only worn for the first 30 minutes and then removed, the result will be 1.

D. Sleep

As far as the sleep analysis is concerned, an implementation of the ”Steady sleep estimation” [35] is used. This algorithm is able to detect the periods of sleep: the date and time of the start of the sleep period, the date and time of the end of the sleep period and the duration in seconds of this interval are considered. An example of raw data acquired from the device is reported in Fig. 1. The management of the patient’s personal data also allows us to record data on the patient’s medical history and physical characteristics such as age, weight, height, sex, device ID and session ID, as well as instrumental measurements already carried out by the doctor to the patient during the physical examination, see Figs. 2, 3, 4. Data exchange with an electronic multimedia record is also in progress [36].

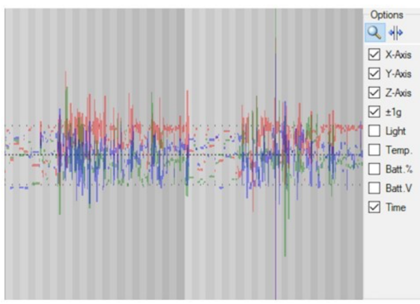

Fig. 1. Example of raw data acquired from the device

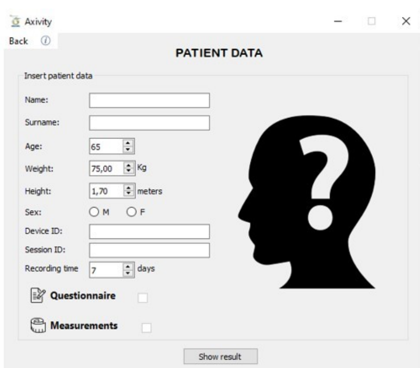

Fig. 2. A subset of patient’s data entry

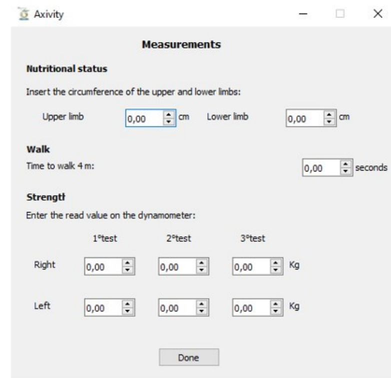

Fig. 3. Patient’s features

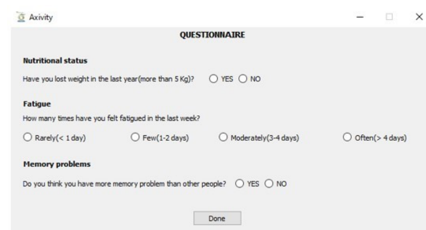

Fig. 4. Patient’s short questionnaire

Fig. 5. General patient’s activity monitoring screen

V. Patient monitoring interface

The patient monitoring screen is divided into five timesections, General, Morning (5:00-12:00), Afternoon (12:0019:00), Evening (19:00-23:00), Night (23:00-5:00). The ”General” section shows information relating to the entire registration period, see Figs. 5 and 6. The information that can be found on the screen is:

- Average number of daily awakenings;
- Average hours of sleep at night;
- Average intensity of physical activity performed;
- Lifestyle (classification by Cut-points);
- Total time the device was not worn;

- Time spent doing low-intensity physical activity; • Time spent doing physical activity with medium intensity;
- Time spent doing physical activity with high intensity.

The following thresholds were considered for the various intensity levels: low (≤ 30mg), medium (≥ 100mg), high (≥ 400mg).

A note is placed in evidence that will indicate whether or not the patient is doing enough physical activity. This information varies based on the time taken to perform physical activity with medium intensity. People over the age of 65 should perform at least 150 minutes of physical activity with moderate intensity. The same information is reported in the following pages, but considering only the relative time frames, in order to differentiate the periods of the day in which the patient is more active and those in which he is more sedentary.

VI. Experiments

For the experimentation carried out in this work, the device was configured by choosing a sampling frequency of 100 Hertz (therefore 100 samples per second), a sensitivity of ± 8g and

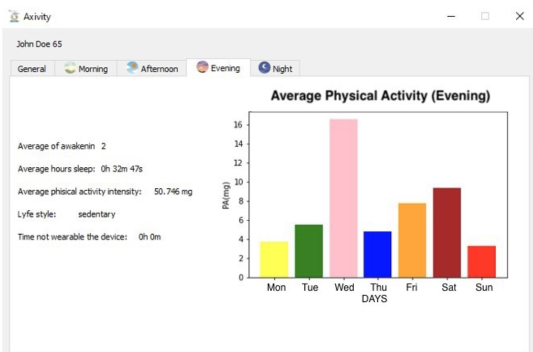

Fig. 6. Evening time window patient's activity monitoring screen

a recording duration of one week. As a sample to test the efficiency of the software, 44 people (22 men and 22 women) over the age of 65 were selected and they were made to wear the AX3 device for a period of one week. At the end of the aforementioned period, the device was returned to the doctor in order to analyze the recorded data.

The age of the patients ranged from 66 to 90 years, including extremes, with an average of 77 years. After using the software to get the values and examining them, we got some information. The average number of hours of sleep was 6 and a half hours. Each individual has unique needs and preferences and the amount of sleep needed also depends on age. In the range we consider (elderly: 65+ years) the recommendation is 7-8 hours but some people may need more or less sleep than recommended based on some factors such as genetics and quality of sleep. Given these factors, we can see that the average is close to the minimum recommended amount of sleep and for further details we should analyze the quality of sleep through other devices.

The average physical activity value among all subjects was 41.876 mg showing how at least a minimum of physical activity is carried out anyway (for example, walking or housework). As regards the various levels of physical activity, it was already evident from the average SVM value that the subjects carried out enough activity with light intensity, some more and some less. Of the 44 subjects, 27 performed at least 150 minutes per week at moderate intensity just as recommended by the World Health Organization (WHO), while the other 17 patients were encouraged to carry out more activity to avoid certain problems. None of the test subjects performed high intensity activities. It should be noted that in most cases the most active patients were the youngest in the sample, which highlights how the age factor influences movement.

Observing Fig. 7 it's also possible to notice how, especially the mean of the minutes spent doing physical activity follow a decreasing trend according to patients age. A slightly similar path is present considering moderate activity too.

All subjects wore the device throughout the week without removing it, in fact on average the device was not worn for about 45 minutes during the entire registration period.

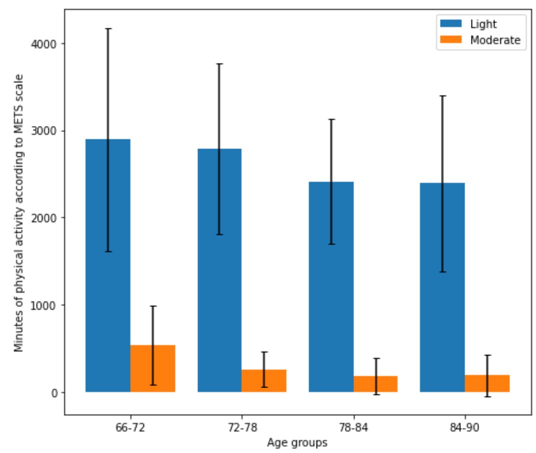

Fig. 7. Means of minutes spent doing physical activity dividing our sample in four age clusters.

This test has shown us how simple it is to collect data on many patients in a short time and make calculations and evaluations on the results obtained. The software created makes it possible to greatly simplify the work of doctors who would otherwise spend hours deciphering the enormous amount of data recorded by the actigraph.

VII. Conclusion

Sleeping, resting well and exercising are essential for our health. It is the condition of efficiency of one's body organism that is experienced individually, depending on the age, as a state of relative physical and mental well-being characterized by the absence of serious disabling diseases. This psychophysical health situation, due to medical advances, is today indicated as the achievement of the best quality and duration of life obtainable by preserving and restoring the state of general well-being.

The aim of this work was the development of a software with a graphic interface that would simplify the operations of analyzing the data obtained using an actigraph. The huge amount of recorded data was used to obtain information on sleep and the level of physical activity of the subject in question. With the use of the software, it will now be possible to examine and obtain information on patients with much greater speed and a reduction in the commitment of specialists, allowing longitudinal monitoring to be carried out on a large number of patients, speeding up also research activity. Our work continues, the integration of information such as temperature and lighting is being studied, information that can bring new knowledge and explain phenomena of excess or lack of sleep or physical activity. The algorithms used are in the basic version and have proved sufficient for this preliminary study, but we intend to design more precise algorithms or to test others already reported in the literature.

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