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Assessment of Emotional States Through Physiological Signals and Its Application in Music Therapy for Disabled People

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ABSTRACT Disabled people have more difficulties for expression and interaction on a non-verbal level because of the physical, sensory or communication difficulties that they usually present. Regarding music therapy, the existing adapted interfaces target disabled people with controlled motor abilities, which still suggests a barrier for the most affected users presenting truly little or uncontrolled movements. In this work, we have developed a device to build an adapted musical instrument through physiological signals. The instrument uses the electrocardiogram (ECG), the electrical activity of the skin (EDA), the respiration signal and the movement of the user to generate music via sonification of the characteristic features of each physiological signal. Furthermore, the ECG and EDA signals have been used to assess the emotional state of the person to provide to the music therapist objective information in real-time about the adaptation of the user to the techniques and interfaces used in their sessions. The adapted instrument has been tested by people with cerebral palsy showing its high degree of adaptability to the user. In four months, an increase in participation of the most affected users in their music therapy sessions has been achieved. In concrete, the results show that the considered users have achieved six of the so-called *aids to analysis* which are commonly used to evaluate such practices. The results of the assessment of emotional states indicate that the state of a person can be extracted from the ECG in periods of ten seconds while the evolution of the EDA reveals if the person is relaxed or excited. The device has generated a lot of interest among educators since it outperforms the state-of-the-art techniques allowing the integration of the most affected users by eliminating the aforementioned barrier because of non-controlled movements while assessing the emotional state of the person when facing the activity.

INDEX TERMS Music therapy, physiology, disabilities, ECG, EDA, adaptability, biometic signals.

I. INTRODUCTION

A huge amount of information related to the psychological state of a person can be retrieved by relying on an analysis of their physiological signals [1]. Thus, the connection between the psychological state of the person and the characteristics of their physiological signals has been studied extensively in recent years. For example, in terms of stress or anxiety, a relationship between chronic stress situations and illness development has been found [2]. Music therapy has been proposed as one of the most effective practices to regulate the balance between the psychological and physiological branches of the human body without relying on medication [3]. Therefore, models relating to both music and emotions based on changes in human biosignals are present in the literature [4]. In addition, music therapy is also used for rehabilitation purposes for people with mental or physical disabilities since it can enhance emotional enjoyment and improve their physical conditions as a result of the plasticity of the brain, which can change and adapt as a result of experience [5]. Music therapy has demonstrated experience-dependent plasticity showing that music stimulates several processes in the brain [6].

This type of clinical intervention with disabled people works towards expression and interaction on a non-verbal level regardless of physical, sensory or communication difficulties, among others. Further clinical benefits include the

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motivational aspects of using such tools in cases where it is difficult to engage in therapy (depressed people and teenagers, among others) [7]. In this sense, common music therapy practices need to be adapted to the necessity of each user in terms of not only the activity itself but also the materials and the musical instruments used. Alternative control interfaces help music therapy by making participation and both artistic and self-expression accessible to disabled people.

On the one hand, in terms of music production, some of the most used elements in music therapy for disabled people are switches. Triggering musical sounds with switches enables the user to play the device as they would play an instrument just by pressing some buttons [8]. On the other hand, regarding music composition, there is also notation and sequencing software that enable users to modify and edit recorded melodies. To use these programs, an adapted mouse or a tracker ball is commonly used [9]. Nevertheless, as can be easily inferred, the vast majority of the available devices and programs require controlled motor abilities such as control over the extremities or the eye blink [10]. Therefore, a barrier remains for the most affected users. Even considering the most commonly adapted instruments, they often lack sensitivity to provide satisfactory feedback in response to minimal movements, or they need to be re-adapted considering the user's needs, when possible [7]. This study revealed that a clear majority of music therapists using adapted interfaces at their work used generated sounds triggered by input devices such as single switches or drum pads, even though they are not accessible to everyone.

The evaluation of adapted technology is always difficult to perform since it depends on several factors, such as the degree of disability of the person, the improvements that the user can achieve in rehabilitation, the observation of the music therapist, etc. Nevertheless, when considering adapted musical technology, the so-called nine *aids to analysis* are commonly used to perform such evaluation. The nine *aids to analysis* were proposed to track the different progressions that the users could experience in music therapy practices when using adapted interfaces [11], [12]. Each of the aids evaluates a behavioral transition that the user should experience as an indicator that the system is helping the user with its rehabilitation. The nine behavioral transitions are *From indifference to interest*, *From involuntary to voluntary*, *From accidental to intended*, *From random to purposeful*, *From gross to fine*, *From isolated to integrated*, *From confined to expressive, From exploratory to preconceived* and, lastly, *From solitary to individual*. Of course, not all the aids need to be achieved to consider that a rehabilitation process has been successful since their accomplishment depends also on the severity of the disability that the person presents and on the training time, among others. Each individual aid should be validated according to their evaluation items and it should be considered individually as a successful step towards rehabilitation.

When assessing the emotional state of a person, one of the most studied physiological signals is the electrocardiogram (ECG), which records the electrical activity of the heart that can be quantified via the heart rate (HR). Studies on how the HR is modified by exposure to music [13]– [15] or even on differences in the shapes of the ECG waves recorded when music is heard [16] have been performed. Another widely used biosignal variation that depends on the psychological state of the person is the electrodermal activity of the skin (EDA), which can be used as an indicator of the levels of stress or anxiety, or even as an emotion recognizer. Thus, this parameter has been used in analyses of the process of decision making, human-computer interactions and video games, marketing and product evaluation, and sleep monitoring, among others [17], [18]. In relation to music, several studies have examined changes in the electric resistance of the skin considering musical stimuli of quiet and classical music versus exciting music [19] as well as considering silence [20].

Although the effect of music and emotions in the human brain has been widely studied through the acquisition and analysis of the electroencephalogram (EEG) of the person [21]– [23], this technique requires, in many cases, a minimum electrode setup of 35 channels in mobile applications [24]. Moreover, the electrodes should be located at exact measurement locations on the scalp, involving a complex set-up and discomfort for the user. In contrast, the selected signals (ECG and EDA) could be acquired by using at most three and two electrodes, respectively, and there are multiple locations at which these signals can be accessed. Therefore, the ECG and the EDA signals were selected as involuntarily modulated physiological signals that are comfortable to measure for both the user and the professional. The use of these physiological parameters also allows a reduction of the preparation time of the music therapy session, which is important if the session is carried out with a large number of users in parallel or if the session is limited in time.

In this work, we present a new adapted musical interface that targets disabled people no matter the severity or the degree of their disability. To overcome the aforementioned problem that people with a severe disability encounters in the current adapted technology, we do not consider the movement as the only way to play with the interface and generate music. In our case, the developed device uses four physiological signals (ECG, EDA, respiratory signal and movement) to generate music according to the proper value of those signals during the sessions. In addition, and due to the fact that the ECG and the EDA signals could be used to asses the emotional state of the person, the device also analyzes the value of these two signals in order to provide to the music therapist information about the state of the person. Therefore, the device could also help the professionals with the adaptation of the music therapy techniques based on the detected level of relaxation or excitement of the users, overcoming the aforementioned limitation in communication. The aim is to adapt and optimize the music therapy sessions individually for each user and to make such beneficial practices available for people with severe disabilities. In addition, the information of the assessment could be also used in non-real time as an objective measure that allows the supervisors to quantify the adaptability of users in each of the learning phases through the continuous supervision of the person's emotional state.

The developed device uses the ECG and the EDA signals not only to produce real-time music according to the detected value, but also to assess the emotional state of the person. Nevertheless, the other two signals (respiration and movement) are used in order to add more features to the music performances and to increase the number of activities in which the device could be used during the music therapy sessions. In addition, it is also interesting to consider these four physiological signals due to the different time scales in which they operate. While changes in HR occur more rapidly in time, changes in the EDA signal require a larger time scale. By adding the respiratory signal, an intermediate signal variation is also added to the system. Moreover, the variation introduced by the movement of the user represents both a voluntary and variable modulation coverage and, therefore, a wide time span. The key point of the analysis of the different time scales relies on the ability to select the biosignals used in the activities depending on the ability of the users and their necessities while controlling overexcitement.

Although the main objective of this work is to develop the adapted musical interface, we first need to recognize the relaxation and excitement states of the users based on the acquired ECG and EDA values. As we want to obtain real-time information of the state of the person, we need to perform the analysis in ultra-short-term recordings of the considered signals. Once this first task is achieved, we can proceed with the development of the portable acquisition system as an adapted musical instrument. The objective is to asses the state of the person and to produce real-time music accordingly promoting the participation of the most affected users since controlled abilities are no longer a determinant requirement.

By examining previous work that considers the ECG in our subject of matter, a study has concretely focused on the influence of music therapy on HRV [15], but this concrete physical information is not being used to generate sounds as in our designed device. A previous system used the HR information to generate music according to the state of the person while working (stressed, bored, relaxed, etc.) [25]. Nevertheless, there are no applications on disabled people. Finally, some studies targeted people with cerebral palsy, but they did not consider the most affected users since the published techniques also require controlled motor abilities [3]. The presented work provides an initial study of the most affected users with cerebral palsy. Regarding the EDA signal, the existing studies do not target disabled people and only consider variations in this signal due to an external stimulus. In this work, we not only study these variations but also use them as musical features of the adapted instrument. Finally, regarding the study of the ECG and EDA signals for assessing emotional states, there are no clear guidelines to detect their variations jointly in short time periods in both the time and time-frequency domains. Therefore, this work presents the following main contributions:

1) A study of the best parameters obtained from ECG and EDA signals that can be used to assess the emotional state of the person for short-duration recording lengths.
2) A pipeline to build a novel adapted instrument for severely disabled people through physiological signals to increase their participation in their music therapy sessions while assessing their emotional state.
3) An initial analysis of the impact of the designed device regarding the evolution of the users during the four months of music therapy sessions.

Concretely, the following sections address the study of the parameters that can be used to determine the individual's condition from short-term measurements of ECG and EDA signals. This first step considers both detection and characterization of the changes in these biosignals because of an external stimulus and shows the models developed to obtain the person's emotional state, which have been validated with experimental measurements on twelve people. Next, the development and testing of the portable acquisition system are addressed as well as the pipeline of the implemented software concerning the output of real-time music generation. To validate this second objective, the system has been tested by four people with cerebral palsy, who were unable to participate in similar sessions previously because of their severe disability, with the objective of promoting the development of their skills in individual music therapy sessions. In addition, the system promotes the integration of the most affected users into the group of musical activities that are normally performed only by users with a lower level of disability. Therefore, our objectives in music-therapy also consider the evaluation of the device in terms of the evolution of the four considered users that has been carried out based on the aforementioned nine *aids to analysis*.

II. ULTRA-SHORT TIME MEASUREMENTS FOR EMOTIONAL STATE RECOGNITION

A. THEORY. EMOTIONAL STIMULI AND NERVOUS SYSTEM

The autonomic nervous system (ANS) is a subdivision of the peripheral nervous system (PNS) that innervates smooth muscle, cardiac muscle and glands and controls involuntary movements [26]. The activity of the ANS represents an average of both the sympathetic and parasympathetic systems. The ANS is also divided into the sympathetic and the parasympathetic or vagal system. On the one hand, the sympathetic system controls *fight-or-flight* responses. It is also activated when dealing with stress situations or because of an intense input stimulus such as music. On the other hand, the vagal system is responsible for *rest-and-digest* activities. The variation in the physiological signals of a person when facing different stimuli encodes information about their psychological state, which is a reflex of the variations in both the sympathetic and parasympathetic systems.

1) ECG SIGNAL

The one-beat ECG wave is characterized by a sharp maximum - R wave - which is widely used as a feature to account for a heartbeat. The time between two successive heartbeats can be obtained by computing the distance between two consecutive R waves (RR interval). Moreover, by analyzing the evolution of this distance throughout an entire ECG recording, the tachogram can also be obtained. Heart rate variability (HRV) is the conventionally accepted term to describe variations in RR intervals. In this work, the RR interval is used for the ECG analysis.

The ECG signal can be evaluated in both the time domain and time-frequency domain in the linear approach [27]. On the one hand, regarding the analysis in time, the standard deviation of the RR intervals (SDNN) can be directly derived from the measurement of the distance between consecutive R waves. The SDNN provides intuition about the cyclic components of the ECG. This parameter is a good indicator of changes in the HR, as it shows the variability of the signal. Other statistical variables related to SDNN are the SDANN and SDNN index. The SDANN estimates changes in HR within cycles of 5 minutes, and the SDNN index provides the mean of the SDNN every 5 minutes of the total recording. Other parameters obtained from the differences between RR intervals can also be derived. The most commonly used parameters include the root mean square of successive differences in RR intervals (RMSSD), the proportion obtained by dividing the number of interval differences of successive RR intervals greater than 50 milliseconds by the total number of RR intervals (pNN50) and the standard deviation of successive differences between adjacent RR intervals (SDSD).

On the other hand, regarding the time-frequency analysis, the characteristic parameters are obtained from the tachogram and not directly from the ECG recording through the continuous wavelet transform (CWT) [26]. In general, the spectrum of the tachogram obtained from the fast Fourier transform (FFT) provides information about the characteristic frequencies of the signal and their corresponding amplitudes and phases. To determine the characteristic frequencies of the signal and the times at which these frequencies occur, a combined time-frequency analysis is needed [28]. One of the most widely used methods for such a combined analysis is the CWT due to the high resolution that it provides. The CWT measures the similarity between a signal and an analysis function. When considering the Fourier transform, the analysis functions are complex exponentials of the form e^{jwt}, while the analysis function in the CWT is a wavelet, Ψ. This method compares the signal to the wavelets. The wavelets are a family of zero-mean functions that are obtained by shifting and compressing (or stretching) a mother wavelet. There are several types of mother wavelets, but the Morlet wavelet has traditionally been used in ECG signal analysis [26]. The CWT can be mathematically expressed as follows:

$$T_x(t, a; \Psi) = \int_{-\inf}^{+\inf} x(s) \cdot \Psi^*_{t,a}(s) \cdot ds \tag{1}$$

$$\Psi_{t,a}(s) = |a|^{-\frac{1}{2}} \cdot \Psi(\frac{s-t}{a}) \tag{2}$$

The parameter a is a scale factor that compresses ($|a| > 1$) or dilates ($|a| < 1$) the wavelet, and the parameter t is used to translate the wavelet. In this sense, the wavelets are modified to use short windows at high frequencies and long windows at low frequencies, increasing the resolution of the outcome. The main problem of using the conventional Fourier transform is that the shortness of the recordings leads to limited resolution at low frequencies, and no solution has been found to overcome this problem without compromising the time variation of the signal. The CWT not only ensures better resolution in the frequency domain for low frequencies (at the expense of losing some in the time domain) but also does not compromise the resolution in the higher frequency band [29].

The main spectral bands that can be distinguished from the spectrum of the tachogram are the very-low frequency component (VLF), considering frequencies below 0.04 Hz, the low frequency component (LF), considering the range of frequencies between 0.04 and 0.15 Hz, and the high frequency component (HF), which ranges from 0.15-0.4 Hz. The spectral power of each band is considered to be the area under the curve, representing the power spectral density bounded to the corresponding frequency band. The total power (TP) can be obtained considering the whole frequency band from 0 to 1 Hz [26]. The major contributor to the HF component is the vagal activity. However, disagreement exists concerning the physiological contributor to the LF component. While some studies suggest that LF is a marker for sympathetic modulations, most view LF as reflecting both sympathetic and parasympathetic activities. Consequently, the LF/HF value, calculated as the ratio of the power in the LF and HF bands, is considered to mirror mainly the sympathovagal balance [30]. Table 1 summarizes how the considered parameters are computed for the ECG analysis in both the time and time-frequency domains.

2) EDA SIGNAL

Human skin displays several forms of biolectric phenomena. These phenomena are especially significant in areas with more sweat glands, such as the fingers, palms of the hands and soles of the feet [31]. The electrodermal activity (EDA) is a collective term used to describe changes in the skin's ability to conduct electricity. Sweat-gland secretion is associated with sympathetic nervous system activity [32]. Whenever one becomes aroused or relaxed, the state is partially translated into sweat production or inhibition at the glands, changing the resistance of the skin.

The EDA signal is caused by two superimposed phenomena: the general electrodermal level (EDL) and electrodermal responses (EDR). The EDL refers to the tonic background component of the signal, while the EDR appears as a result of rapid phasic or response components due to tissue changes when initiating eccrine sweat-gland activity. In general, the signal is constant regarding the EDL and

TABLE 1. Parameters for the study of the ECG signal in the time and time-frequency domains in the linear approach.

SDNN = $\sqrt{\frac{\sum_{n=1}^{N}(RR(n)-\overline{RR})^2)}{N-1}}$ where N is the number of RR intervals
RMSSD = $\sqrt{\frac{\sum_{n=1}^{N-1}(DARR(n)-\overline{DARR})^2)}{N-2}}$ where $DARR = \|RR(n+1) - RR(n)\|$
SDANN = $\sqrt{\frac{\sum_{n=1}^{L}(RRm_{5min}(n)-\overline{RRm_{5min}})^2)}{L-1}}$ where L is the number of intervals of 5 minutes
pNN50 = $\frac{\sum_{n=2}^{N}V(n)}{N}$ where $V(n)$ is one or zero if the time between consecutive RR intervals is larger or smaller than 50 ms, respectively
$\text{SDNN}_{Index} = \frac{1}{L}\sum_{n=1}^{L} SD(n)_{5min}$ where SD is the standard deviation
SDSD = $SD(DARR(n) - \overline{DARR})$
LF(n.u) = $\frac{LF}{TP-VLF}$ where TP is the total power and VLF the very-low frequency component.
HF(n.u) = $\frac{HF}{TP-VLF}$ where TP is the total power and VLF the very-low frequency component.

increases because of the EDR. The polarization properties of the skin also produce fast-recovery EDR components that are related to a stimulus prior to their occurrence [32]. The EDA signal is commonly analyzed in the time domain by capturing the changes in the signal level due to the EDR with respect to the EDL.

The variation in these two physiological signals has a clear impact in the autonomous nervous system. In terms of the HR, when an external stimulant is present, the sympathetic system acts by increasing the HR. When the stimulus disappears, the parasympathetic branch takes over, reducing the HR. These changes are also a reflection of the respiratory signal, the rate of which increases when aroused and decreases when relaxed. In terms of the EDA signal, the same behavior of both the sympathetic and parasympathetic systems occurs, decreasing and increasing the electrical resistance of the skin, respectively.

B. MATERIAL AND METHODS

Some experiments were performed to determine how the ECG and EDA signals are affected by an external stimulus with respect to the obtained values at rest.

The designed experiment consisted of monitoring the subjects in three periods of 5 minutes since it is the length of the standard ECG recording (gold standard) [27]. During the first period, the subject was told to be at rest in a relaxed position. During the second period, the subject was monitored while listening to exciting music in the same relaxed position as before. To explicitly explore the whole range of variability in the subjects, they were also submitted to a *Stroop test* while listening to music. The final part of the experiment also consisted of a five-minute resting period, expecting the signal to recover the characteristics measured during the first period. Half of the subjects performed the experiment twice on different days. Additionally, half of the subjects were randomly selected for an additional fourth period of stimulating music. The aim of adding a new period of excitement was to demonstrate that the observed changes appeared with the external stimulus and not because of other factors. In other words, the repeated exposure allowed one to determine that the results were reproducible when faced with the same stimulus.

Both signals were acquired by the commercial device Biopac MP36. This acquisition system has a microprocessor to control data acquisition from four analog input channels of 24-bits with a modifiable sampling rate [33]. Once the signals were acquired, they were also processed and characterized according to a Matlab routine of feature extraction that will be presented in the following section.

Twelve subjects were subjected to this first experiment, namely U1-U12. The ages of the subjects ranged from 21 to 41 years old with an average age of 24.5. All the considered subjects were monitored in terms of the ECG signal. The EDA signal of six subjects was simultaneously recorded during the experiment. The ECG recording was carried out by placing one electrode on each arm and a third one in an electrically neutral zone such as the ankle. For the EDA recording, electrodes were placed either on the forearms or the palms of the subjects.

Processing routines were implemented with Matlab to process the signals acquired with the Biopac MP36 system and to extract the desired information. In terms of the ECG signal, R waves were detected using the Pan-Tompkins algorithm [34]. The implementation of this algorithm in the Matlab software was carried out considering filtration, derivation, squaring, integration and adaptive threshold for R wave detection [35]. Moreover, a decision rule was applied to search for possible missing QRS complexes and to eliminate the detection of multiple R waves within an anomalous time period. As observed in Table 1, all the parameters analyzing the signal in the time domain are based on the RR intervals. Therefore, after a successful detection of the R waves, it was possible to compute these parameters and compare them for each of the recorded periods. For the time domain analysis, the computed

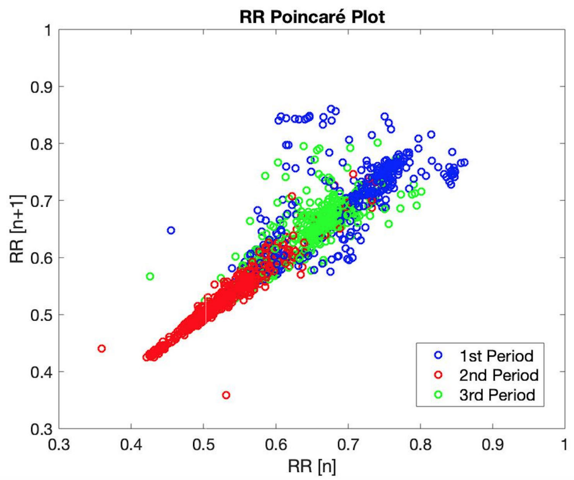

FIGURE 1. Poincaré plot of U1 by means of the ECG signal. The three periods of the experiment were distinguishable due to the increase in HR when faced with an exciting music stimulus. Blue: Scattered points corresponding to the first resting period. Red: Scattered points of the period where the stimulus is present. Green: Last resting period showing the recovery of the signal.

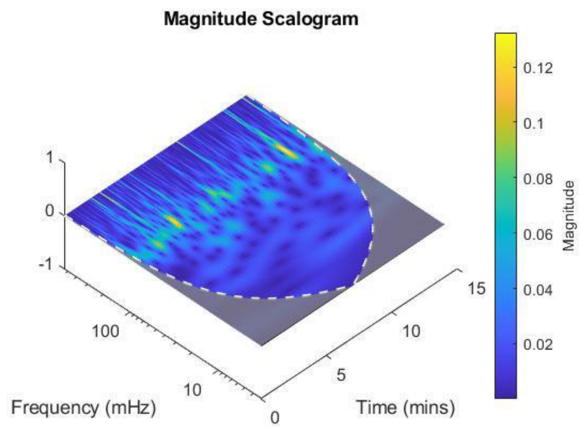

FIGURE 2. Time-frequency-magnitude representation of the tachogram obtained from the ECG signal during the experiment. An increase in magnitude could be observed in the frequency range of the HF during the resting periods, indicating an enhancement of parasympathetic activity, which is related to relaxation.

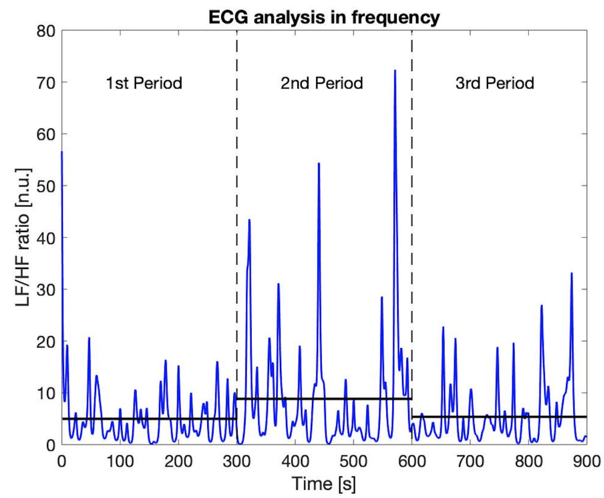

FIGURE 3. Evolution of the ECG frequency ratio over time for U1. The time-frequency analysis showed how the parasympathetic activity was reduced and the sympathetic activity was increased during the stimulating period.

parameters were SDNN from the RR interval and RMSSD and SDSD from the subtraction of consecutive RR intervals. The other parameters were discarded due to the necessity for larger recording lengths. Moreover, the number of beats-per-minute (BPM), mean RR interval and number of R waves detected in an interval of ten seconds were also computed.

To analyze the EDA signal, the implemented routine fits the behavior of the signal when musical stimuli are present by considering a linear model. Hence, the slope of the line of best fit for the signal in each of the recorded periods was computed. This analysis provides a way of detecting relaxation and arousal based on recognition of the characteristic patterns described when the signal evolves over time.

C. EXPERIMENTAL RESULTS

In terms of the ECG signal, all the considered subjects experienced arousal during the stimulating period. Excitement was observed due to the decrease in the RR interval (Figure *1*), leading to an increase in BPM. In terms of the SDNN, RMSSD and SDSD parameters, the general tendency was to show less variability in the R waves when aroused. Eight of the twelve considered subjects showed this tendency in the first day of measurement. Four of the six that repeated the experiment on a second day also matched the general trend. Mismatches between the considered intervals were found on the first day in four of the considered subjects, and two of them maintained this tendency on the second day. Finally, repetitivity was found in half of the considered subjects.

In the time-frequency domain, the general tendency was an increase in the $\frac{LF}{HF}$ ratio, indicating enhancement of the sympathetic activity, which is related to arousal. This tendency was shown in nine of the twelve considered subjects on the first day of the measurements. Three of the six considered subjects showed this pattern on the second day of measurement. Finally, mismatches between the considered periods were found in one subject.

Figure *2* shows the 3D time-frequency-magnitude representation of the tachogram obtained through the CWT of the signal of one of the considered users. An increase in magnitude could be observed in the frequency range of the HF components, especially during resting periods (from 0 to 5 minutes and from 10 to 15 minutes in the frequency range from 0.12 - 0.38 Hz). This pattern showed the expected increase in parasympathetic activity during the resting periods, producing a decrease in $\frac{LF}{HF}$ ratio.

To clearly observe the evolution of the $\frac{LF}{HF}$ ratio throughout the activity, it is interesting to observe a section of the 3D representation considering only frequency and time. Figure *3* shows the evolution of the $\frac{LF}{HF}$ ratio over time. The aforementioned increase in the $\frac{LF}{HF}$ ratio during the

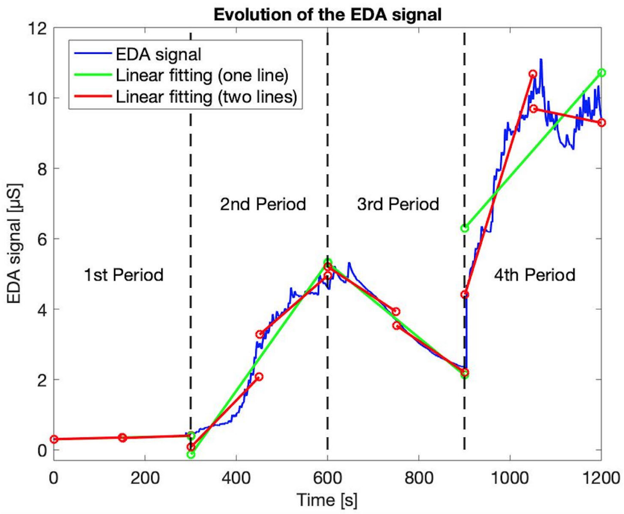

FIGURE 4. **Evolution of the EDA signal for U1 during the experiment with a fourth additional exciting music period. The representation shows the lines of best fit considering one (green line) or two (red lines) stages within each period.**

exciting music period could be observed. Figure *3* shows the general pattern presented by the acquired ECG signal during the experiment when treated in the time-frequency domain. The time-frequency analysis provides an understanding of the adaptability of the person to the activity being performed. The person becomes excited when the activity is hard. This analysis can be applied not only to music but to other daily activities.

The analysis in the time domain of the EDA signal performed by considering the slope of the line of best fit showed the desired result of distinguishing resting from arousal periods. Figure *4* shows the original signal and lines of best fit for each period. As can be observed, the first resting period was characterized by a flat line (see Figure *4*, period 1), the slope of which started increasing once the stimulus started (see Figure *4*, period 2). During the period of excitement, one could also observe that the line became flat after increasing to a certain magnitude, which occurred when the person becomes accustomed to the stimulus (see Figure *4*, period 4). When the person passed from a period of excitement to a resting period, the slope of the line of best fit started to decrease (see Figure *4*, period 3). We hypothesize that the same effect of becoming accustomed to the new stimulus (or a lack of stimulus in this case) should be presented in the form of a flat line if one extends the resting period. Almost all the users showed this tendency. The only mismatches found were for one user for whom the fourth additional period was also considered.

From this analysis, it is possible to distinguish the periods of excitement of a person from the periods at rest via the ECG and EDA signals. Concretely, by using the SDNN, RMSSD and SDSD parameters for the ECG analysis in the time domain, more variability can be observed in the periods of excitement with respect to the values at rest. Regarding the ratio between low and high frequency components, one can observe that the ratio increases during periods of excitement with respect to the values at rest. Finally, by examining the characteristic pattern of the EDA signal, one can note that ascending slopes correspond to periods of excitement, while descending slopes and flat regions correspond to recovery and initial rest, respectively.

Biosignals can be used to determine the state of the person. Nevertheless, another key point is to determine how much the time of recording can be reduced to access the desired information. In terms of the EDA signal, we can use the values of the signal in real time since we rely on the form of the electrical wave. Nevertheless, regarding the ECG signal, we must estimate the aforementioned parameters. Therefore, an ultra-short analysis of the ECG signal is needed.

In the experiment, the SDNN and RMSSD parameters showed larger variations between periods. To estimate these parameters from short recording lengths, a combination of both statistical and correlation tests is required [36]. Twelve subjects were randomly selected and their ECG signals acquired for 20 minutes in a relaxed position. Then, the recordings were divided into four periods of five minutes. The SDNN and RMSSD parameters were computed within 30 intervals of 10 seconds and throughout the whole 5-minute segment. To evaluate whether the accuracy increased with the recording length, both parameters were computed for time intervals of 30, 90 and 120 seconds.

One interval of ten seconds was randomly selected, and the computed parameters were compared with those obtained from the gold standard (5 minutes long). The same random selection was also applied when considering different recording lengths. For all recording lengths, the correlations obtained from RMSSD considerably outperformed those obtained from SDNN. In particular, the correlations were significantly small for intervals of 10 seconds regarding the SDNN parameter. This result led us to conclude that SDNN could not be estimated in the desired short time period [37] and therefore could not be used to access the information in a reasonably short time. The obtained correlations for RMSSD presented a wide variability between 0.40 and 0.99. The agreement increased with recording length, reaching nearly perfect agreement beyond 120 seconds. The variance also decreased with increasing recording length.

The correlations were verified with a Bland-Altman plot. In the case of 10 seconds, a bias of -0.0015 s and an SD of ± 0.0036 s were observed, with limits of agreement located at $+0.0056$ s and -0.0085 s. Therefore, the limits applied to distinguish arousal from relaxation should not be less than the 8.5 ms error computed herein. When computing the Bland-Altman plots for recording lengths of 30 s, 90 s and 120 s, the bias also decreased as the recording lengths increased. Cohen's d statistics was also calculated to quantify whether the information retrieved from the randomly selected interval of 10 s was the same as that provided by other 10 s intervals during the correlation test. To achieve this goal, the differences in the mean of each interval were divided by the standard deviation of the total recording. Analysis of the obtained data revealed a mean Cohen's d of 0.3146 with a variance of 0.0978. In this particular case, a Cohen's d of 0.3146 could be interpreted as a small-moderate effect [38]. Therefore, the information obtained from any of the 10-second intervals could be comparable to the information obtained from gold standard recordings.

In the time-frequency domain, the LF component has a frequency of 0.04 Hz, which corresponds to a period of 25 s. The recording should last for at least 10 times the wavelength of the component to obtain reliable information [27]. A total recording of 250 s is then needed to achieve reliable data for this frequency component. Similarly, for a good estimation of the HF component, at least 60 s of recording is required. Therefore, a reliable ultra-short duration analysis could not be performed when analyzing features in the time-frequency domain.

This short-time analysis revealed the possibility of assessing the state of the person by analyzing the ECG signal in the time domain and the reliability of this information from 10 seconds onward. Finally, although we cannot assess the state of the person in real time (or in ultra-short time recordings) by analyzing the time-frequency domain, we can use this information to complement the analysis in time domain and to supervise the evolution of the user from one session to another (continuous supervision).

III. ADAPTED MUSICAL INSTRUMENT

A. MATERIAL AND METHODS

Because of its size, weight and cost, the Biopac MP36 used in the section above is not suitable as a system for ambulatory measurements for rehabilitation and recreational activities. Thus, we designed a new hardware system to accomplish our requirements.

The acquisition of the ECG signal was carried out by using the commercial module Bitalino, while a proprietary module was designed for the EDA signal. The ADC used is also the one provided by the Bitalino board. This commercial board achieves a maximum sampling rate of 1000 Hz and has four input ports of 10 bits and two others of 6 bits. Moreover, it has a built-in Bluetooth connection as a wireless technology to easily transfer the recorded data [39].

The module acquiring the ECG signal has a gain of 1100 in magnitude and an output range of ± 1.5 mV with an input voltage of 3.3 V. Moreover, the acquired signal is filtered between 0.5 and 40 Hz to avoid interference due to the respiratory signal, which lies between 0.12 and 0.5 Hz [40], or the 50 Hz interference of the power supply. The ECG module has been validated in comparison to the medical device Biopac MP36. The overall analysis shows a bias of -0.2556 bpm and a standard deviation of ± 0.5216 bpm. Therefore, both devices could be suitable for this concrete application where no medical diagnosis is expected.

To measure the EDA signal, a compact and portable electrodermal activity measurement system was designed and implemented based on a circuit presented in [41]. It achieves

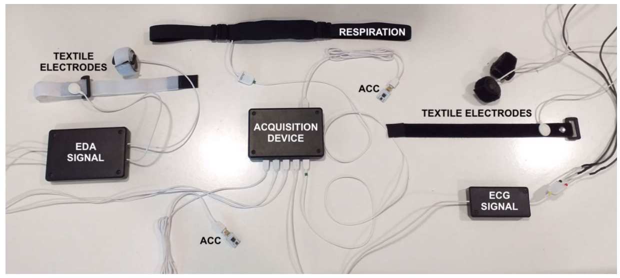

FIGURE 5. Acquisition device with the described hardware implemented in a compact way.

the required accuracy by individually amplifying the slow and fast electrodermal effects EDL and EDR, respectively. As considered with the ECG signal, the commercial module for the acquisition of the EDA signal was used first. Nevertheless, this acquisition system was found to filter the signal within a band-pass from 0 to 3 Hz, while several studies have advised filtering the signal from 0 to 35 Hz to capture the information related to subtle changes [42]. The designed system achieves the theoretical frequency range.

Electrodes were used to measure the biosignals from the body surface. Proprietary textile electrodes were developed using a conductive yarn made of silver filaments, which is attached to a textile insulator material. The performance of the textile electrodes was checked against the traditional electrodes of Ag/AgCl, recording the ECG signal in equivalent positions. In comparison, the textile electrode acquires the signal from a larger surface, so an integration over the whole area in performed. As a result, the output signal is less noisy due to the low-pass filtering behavior of the integral, but it could be perfectly suitable for our implementation.

Finally, all the developed systems were integrated together to form the device shown in Figure 5.

The results of the variability analysis point towards changes in the considered signals depending on the state of the person. The different states of the person were studied in the section above by submitting the subjects to different stimuli. At this point, regarding the noticeable effect of the stimulus on the considered signals, the option of using the designed hardware and the variability analysis to implement an adapted musical instrument for people with disabilities was explored.

The idea behind the music instrument was to use the heartbeat of the users to establish the rhythm of the musical performances. In addition, the melody of the performance could be made based on the changes in the EDA signal, as it is a signal that is fully related to the emotions that may arise during the activities. Given the versatility of the device, two accelerometers were added to the system to characterize movements of the extremities of the users, if controllable. Additionally, a piezoelectric sensor was also added to measure the respiratory signal and use its characteristic features in the musical performances. It is interesting to note that, from the music therapy perspective, the aim is to allow users to realize that the musical features of the performance are made by them and that the variability in the music is related to their own movements or feelings. Therefore, the musical features could be classified as passive or active and could be selected depending on the user ability.

A Matlab script was developed to allow detection of the heartbeats in real time through the Pan-Tompkins algorithm. The changes in resistance of the skin, movement of the subject and respiratory wave were also processed in real time. Both the movement and respiratory signals were triggered at a certain personally calibrated value. All the computed information was sent to the software music sequencer -Ableton Live- to transform the characteristic parameters of each signal into musical features. The link between Matlab and Ableton Live was achieved using a third linking software named Pure Data.

Both the accelerometers and the piezoelectric sensor used for the recordings were provided by Bitalino. The signal obtained from the accelerometers has a frequency bandwidth of 0-50 Hz and an output range of ±3g, and changes are considered with respect to the Z-axis. The acquired signal was low-filtered in the frequency range from 0-10 Hz. This bandwidth was sufficient to eliminate involuntary trembling of the users and noise [43]. In addition, a median filter was applied to smooth the signal and eliminate involuntary movements enhancing the voluntary ones [44]. The respiratory signal was detected through deformations of the piezoelectric material during inhalation and exhalation because of the movement of the rib cage. This acquisition module filters the signal within the frequency band of 0-15 Hz, and no further processing was required. It is interesting to note that the respiratory signal could be extracted from the ECG signal by the breath rate demodulation technique [45].

Four users with cerebral palsy gained experience with the designed device in music therapy sessions of the Aspace Catalonia Foundation (Figure 7) on different days with continued supervision. The ages of the users ranged between 23 and 40 years old, and the mean age was 29.8 years old. Table 2 describes the main affectations of the considered users due to the cerebral palsy from which they suffer.

The electrodes were located on the arms of the subjects at the positions shown in Figure 6, and the device was integrated into a wheelchair. The breathing sensor was located on the chest via an elastic band, and the accelerometers were sewn into gloves, wrist and elbow pads to ensure a quick adjustment for each user.

B. EXPERIMENTAL RESULTS AND DISCUSSION

Before the introduction of the designed device, the four considered users could not participate actively in the music therapy sessions of ASPACE since all the adapted interfaces that were available (switches and drum pads) required controlled motor abilities. The activities with the four users lasted four months and revealed a growing awareness as the number of sessions increased. There was also an increase in participation indicative of the development of mental and physical control abilities. The evolution of the four users was evaluated considering the nine *aids to analysis*, which were proposed to provide clear pointers and indicators for progression and development in such activities [11], [12]. These aids show transitions between behavioral states of the users due to activities as their frequency increases. In the considered case, six of the nine aids were met over the four months:

- **From indifference to interest:** Increasing interest and awareness were found regarding the device in the music therapy sessions. Initially, the four users showed indifference or even nervousness that transitioned into interest in three cases. The user that does not achieve this aid showed always indifference when starting the sessions. The evaluation items used to validate this aid were: 1) The users shows pleasure or happiness when being brought from the common classroom to the session, 2) The user starts making patterns of movements even before the device is connected. This aid was achieved during the first two weeks.
- **From involuntary to voluntary:** Regarding three of the considered users, the movements that were initially spasmodical were transformed into extended periods of stillness. The evaluation items were: 1) An increasing number of periods of stillness, 2) The users shows voluntary on-off control of the movements. The user that does not achieve this aid did not achieve the second evaluation item. This aid was achieved by the other three users at the end of the first month and beginning of the second one.

TABLE 2. Description of the main affectations of the disabled users that tested the designed device.

Main affectations	Users
Stiff muscles and exaggerated reflexes. (spasticity)	U1, U2, U3
Stiff muscles with normal reflexes. (rigidity)	U4
Tremors or involuntary movements.	U1, U3
Difficulty with fine motor skills.	U1, U2, U3, U4
Speaking difficulties.	U1, U2, U3, U4
Problems with swallowing.	U3, U4
Difficulty with sucking or eating.	U1, U2, U3, U4

FIGURE 6. Position of the electrodes during the measurements.

FIGURE 7. Cerebral palsy users performing recreational and rehabilitation activities with the implemented device.

- **From accidental to intended:** The users developed a relation between a concrete movement and a concrete sound. Initially, sound was generated by involuntary movements. Patterns between the different emotional states detected through the ECG and EDA signals and their associated sounds were also created. The evaluation item considered for validating this aid was the creation of at least one patter per user. This aid was achieved during the second month.
- **From random to purposeful:** The users showed the creation of patterns of movement from week to week to reproduce certain sounds. This aid extends in time that of *From accidental to extended*. The evaluation item used in this case was regarding the ability of the user to reproduce at least one concrete patter each session over at least three consecutive days. One user also showed purpose in the respiratory signal. This aid was achieved at the end of the second month and beginning of the third one.
- **From gross to fine:** During the initial experiments, the users were able to control movements as a switch (off/on sounds). At the end of the four months, there were more nuances in the type of movements and their associated sounds. The evaluation item was whether the music therapist could increase the number of sounds by increasing the sensibility of the transition and the user was still able to reproduce all the sounds of the scale or not. This aid was achieved during the third month but also reinforced during the fourth month.
- **From isolated to integrated:** Once the users progressed to controlling the device, we started the integration of the single individuals into group musical activities. Concretely, usage of the ECG signal generated a lot of interest in the other participants of the performance that presented a smaller degree of disability, increasing the integration of severe users. This aid was validated thanks to the creation of an order of instruments in the performance and due to the fact that the users were able to participate only when planned. This was the last one to be achieved and was addressed mainly in the fourth month.

The six aforementioned aids were the ones achieved by three of the considered users during four months of music therapy sessions while the other user achieved five of them. The other three *aids to analysis* that were not achieved are presented below. Based on the opinion of the music therapist in charge of performing the test phase of the developed device, the following aids were too complex to be achieved by the four considered users due to the severity of their disability. Nevertheless, we expose the other three aids to give a guideline on how to evaluate them for future users:

- **From confined to expressive:** This aid evaluates the expressive use of sound. The evaluation item was to check whether the user was able to take control of the situation and produce sounds exclusively by its own. This aid was not achieved since the users always needed incentives of the music therapist or the environment to produce sounds. They did not take control of the situation during the four months.
- **From exploratory to preconceived:** This aid evaluates the ability of the user to stay at least one session of 30 minutes voluntarily producing sounds that were already known. In other words, the evaluation item used was if the user could perform at least one session without an exploration phase. This aid was not achieved since all the users were always exploratory at all the sessions.
- **From solitary to individual:** This final aid tries to identify if the user is able to communicate through music in the sessions. In order to verify this aid, the evaluation item proposed was if there was a clear relation between a sound and the emotional intention of the user.

This aid was not achieved since the music therapist did not encounter clear communicative intentions through sounds in the considered users.

Finally, because the designed device can assess the person's emotional state in short-term periods, the intensity of the music therapy sessions could be modified according to the detected state in quasi-real time. Therefore, the professionals can prevent overexcitement (or boredom) by modifying the activity when it is too difficult (or too easy) for the user.

IV. CONCLUSION

This work establishes a pipeline to build an adapted instrument through physiological signals. However, it also provides insight into the possibility of assessing the state of a person by monitoring the user in short-term periods. On the one hand, biometric signals can be used to determine the state of the person, which could be used for communication purposes; on the other hand, biosignals can enhance participation, opening new avenues for controlling environments or interfaces.

It has been demonstrated that it is possible to distinguish between the states of relaxation and excitement of a person by relying on ECG and EDA signals, concretely, by computing the RMSSD parameter within a 10-second recording of the ECG signal with ± 0.0036 s of deviation and the slope of the line of best fit of the EDA signal in real time. The analysis of the ECG signal in the time-frequency domain showed the possibility of distinguishing between the two states but with longer recordings. Therefore, it cannot be used in our music therapy applications with disabled people because they require real time.

One of the advantages of this work is that the adapted instrument achieved the desired conditions of easily wearable and comfortable, adaptable, non-intrusive and cost effective. It can be easily located on a wheelchair or even carried. Another advantage is the wireless communication feature that it presents that facilitates its usage. Moreover, its versatility allows one to connect only the desired sensors but is open to other acquisition modules apart from those presented herein. The main disadvantage of the device is that an adequate acquisition of the ECG signal should be guaranteed for a correct performance of the device. To overcome this disadvantage, several electrode locations were explored during the project to provide different adaptations regarding the necessities of each user. Nevertheless, the correct performance still depends on a successful ECG acquisition in order to assess the emotional state of the user. Another disadvantage regarding the EDA signal is that it must be calibrated for each user to explore the whole range of variability in each person. Nevertheless, as an advantage, the calibration process is quicker than for other biosignals such as the EEG. Finally, there is also a disadvantage regarding the acquisition of the respiratory signal since it is acquired by using a piezoelectric sensor located at the thorax of the users. This method cannot be used for all the users since most of them present scoliosis. Future work should focus on the acquisition of the respiratory signal through non-contact methods. Nevertheless, as mentioned above, we have already started to address this issue since the respiratory signal could be extracted through monitoring of the ECG signal using the breath rate demodulation algorithm. All these alternatives to the disadvantages of the current system clearly demonstrate the flexibility of the developed device.

The designed device was tested by people with cerebral palsy, showing its high degree of adaptability to the user. In four months, an increase in participation in the music therapy sessions of the most affected users was achieved. Thus, the most affected users were finally integrated into group musical activities and participated in a public music concert with all their colleagues at the ASPACE Catalonia Foundation, regardless of their level of disability. The device has generated great interest among educators since the adapted instrument represents a novel way to perform both recreational and rehabilitation activities with disabled users by adapting the system to their needs. Concretely, the device has achieved the following transitions between behavioral states in the rehabilitation process of the considered users: from involuntary to voluntary, from accidental to intended, from indifference to interest, from random to purposeful, from gross to fine and from isolated to integrated. Finally, because the ECG and EDA signals of the adapted instrument can be used to determine whether the user is excited or relaxed, the designed device also allowed the adaptation of music therapy activities based on the feedback provided by the system regarding the emotional state of a user without verbal communication.

The state of the person is an indicator of emotions that could be used to assess the user's adaptability to different tasks. This is a powerful idea that has been used in the adapted instrument in this concrete case, but it could be used for several different purposes with people presenting communication difficulties.

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