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Body posture determination for Heart Failure patients from ankle orientation measurements

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ABSTRACT Heart-Failure (HF) is among the leading hospitalization causes in modern healthcare systems. In this paper, a method for performing continuous patient monitoring is presented with a focus on low power consumption. A prototype wearable device is being developed at the University of Sevilla to collect measurements. Among the sensing components there are two major blocks formed by a commercial biological impedance analog frontend from Analog Devices (AD5940) and an Inertial Motion Unit (IMU) capable of estimating attitude of the device. This information could provide a tremendous amount of information for the physician and help diagnose and remote monitor patients with HF. A major factor that can be analyzed to provide information on patient status is activity level and body states; time spent walking or standing, laying down or seated. In this work, a body tracking / activity estimation method is proposed for low power continuous monitoring. This study reports good results characterizing the laying down position and discriminating between laying down and standing/walking and seated. The presented results are relevant for clinical practice since body motion and position can serve as a health marker for patients. Additionally, the acquired motion information can be further processed to better understand artifacts and variations in the analog impedance measurements.

INDEX TERMS Body tracking; Position estimation; Patient activity; Low power monitoring

Heart Failure (HF) is a life-threatening disease that appears as a result of different heart diseases [1]. The diagnosis of the condition is performed in part by observing body signs such as dyspnea and swelling of the legs, which are a direct consequence of deviation from the correct cardiac function or structure [2]. Heart-failure is a condition that has a huge impact on the entire healthcare system. This condition is the leading cause of hospitalization in people over 65 years of age [3]. The impact is estimated to be on approximately 2% of all healthcare resources in Europe [4]. Furthermore, if the disease becomes critical, a condition known as acute decompensated HF, the patient is in a life-threatening high-risk situation that requires continuous hospitalization and emergency treatment to manage excess and accumulation of liquid [2].

Recently, the monitoring of leg volumes [5] has been proposed as a novel method to evaluate the evolution of HF patients. A potential noninvasive technology to evaluate this liquid accumulation is based on impedance measurements. This is an interesting approach due to the value as a biomarker of biological impedance showing a direct association with HF risk [6]. Among patients with HF, edema tends to form in the lower extremities due to the effect of gravity. In this context, continuous monitoring of tissue impedance located near the ankle would potentially allow one to monitor this liquid retention and hence to provide a better management of the HF condition by analyzing changes over time.

These volume changes, however, are a consequence of multiple factors such as heart function, body orientation, and activity of the patient. Therefore, in this context, to understand if the volume change or the cumulative tendency implies a clinical emergency, an additional method is required to evaluate body position. In this paper, an estimate of activity level (as a measure of how much time the patient is active throughout the day) and body positions (laying down, sitting, standing, walking) is proposed through an analytical method. The importance of an accurate body tracking estimation is to provide a better understanding of the impedance measurement and the impedance-based local volume changes acquired with the wearable device.

A growing body of scientific literature has studied the use of wearable devices to support clinical practice. An overview of the use of wearable devices and sensors in Parkinson's disease has been studied in [7]. Monitoring can be performed for Parkinson's disease patients for several purposes: assessment of the patient's motor status before and after therapy, evaluation of motor characteristics, and detection of complications, among others. These kinds of device can also be used to diagnose the disease early in a potentially at-risk population. The authors of [8] have also studied the use of wearable devices in Parkinson's disease in the literature. They found that the most common type of wearable sensor was a six-axis Inertial Motion Unit (IMU), a device which is similar to the one implemented in the prototype proposed in this paper.

Wearable technology has also been used to monitor disabilities such as motor impairment, vision and/or sensory loss, and bowel and bladder dysfunction, in patients with multiple sclerosis [9]. Limitations identified in this review are related to improper sensor placement and patient adherence. Wearable technology has also been studied for the detection and monitoring of mental health conditions and stress [10]. In addition, wearable technology has also been widely studied for cardiovascular disease. In [11], authors propose a wearable device for monitoring and control of blood pressure in pregnant women. Data were collected by mobile phone and then stored in a remote database. The information was then made available in real-time for physicians. The authors in [12] have remotely captured data from six-minute walk tests perfomed by patients with cardiovascular diseases. This type of test is a clinical assessment of the prognosis and clinical status of these patients. The results showed that this type of technology provides accurate and meaningful insights into clinical practice and serves as a powerful evaluation tool of the patient's clinical status.

The most common commercial wearable devices are reported nowadays in [13]. Activity and biometric sensors such as accelerometer, barometer, Global Positioning System (GPS), photoplethysmogram, electrocardiograms and oscilometry are being used for a variety of measurements: step count, impact force, speed, exercise, heart rate, sleep, arrhythmia, among many others. Clinical applications are numerous: prediction, management, and diagnosis of different heart conditions, such as HF, hypertension, acute coronary syndrome, among others.

There has also been a growing interest in the use of body tracking for patient monitoring. The authors of [14] used clinical data and an IMU-based wearale to monitor health changes in patients with congestive HF. In [15], older HF patients and healthy individuals wore an IMU system on both ankles while performing mobility activities (walking, balancing, sit-to-stand transfer). Body tracking can also be performed vision-based, using a camera paired with artificial intelligence (AI) algorithms [16].

Our proposal is to enable a prototype wearable platform to acquire motion information through an IMU device, the sensor chip is Bosch BNO055 [17]. This wearable platform is implementing a biological impedance analog frontend to perform volumetric measurements in local tissue regions near the ankle. In addition to the impedance measurement the IMU sensor will capture orientation and provide the input to our analytical method periodically. Both biological impedance and motion measurements are synchronized. In terms of energy, the power consumption in the device is pretty low due to the measurement protocol established (15 minutes between measurements) and the adequeate electronic design to power off everything except the microcontroller. The entire developed system is currently being tested at the Hospital Universitario Virgen del Rocío (HUVR) for clinical validation.

I. MATERIALS AND METHODS

The work presented in this article uses quaternions [18] as the mathematical tool to explore and analyze body postures from the reported attitude measurements of the IMU device. The following section introduces the equations and relations governing the orientation measurements from the perspective of a known reference frame; in our case, earth's local tangent plane.

The Bosch BNO055 sensor [17] has a wide range of configuration options to retrieve several motion parameters, including acceleration, gyroscope, and magnetometer across all three axes. Additionally, the device is capable of performing data fusion estimation of the orientation with respect to the earth's local tangent plane. This information can be provided in two different formats; Euler angles and quaternions. Due to the avoidance of the gymbal lock effect, quaternions are selected as the best representation to perform these measurements from the ankle.

A. SENSOR ATTITUDE AND SPATIAL ROTATION

The attitude measurements expressed in the form of quaternions that the IMU sensor provides are a representation of the rotation of the device with respect to the reference frame of the earth (LTP). This rotation as was mentioned previously is expressed in the mathematical form of a quaternion. A quaternion (q) is formed by a unitary vector multiplied by a scalar ($sin(\frac{\theta}{2})\overrightarrow{v} \epsilon \mathbb{R}^3$) and a scalar magnitude ($cos(\frac{\theta}{2})$). θ represents the angle of rotation around the unit vector $\overrightarrow{v}$.

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$$\overrightarrow{v} = [\ q_1 \quad q_2 \quad q_3\ ] \qquad q_0 = cos(\frac{\theta}{2}) \tag{1}$$

$$q = [\ cos(\frac{\theta}{2}) \quad sin(\frac{\theta}{2}) \cdot \overrightarrow{v}\ ] \tag{2}$$

Where:

$$|q| = 1 \tag{3}$$

From the sensor attitude measurements, the problem to be addressed is finding the relationship between the device reference frame (ankle orientation) and the Earth Reference Frame. To achieve this purpose, the quaternions algebra serve as a potent useful tool which easily rotates coordinates from a reference frame a second reference frame. An extensive analysis of this problem and the full description of the mathematical method employed to translate across reference systems can be found in [19], where the authors initially explore the basic aspects of body tracking from an ankle-positioned device.

The mathematical relation between a vector defined in the ERF ($\overrightarrow{u}$) and a vector defined in the SRF ($\overrightarrow{v}$) can be expressed as:

$$\overrightarrow{v} = q \odot u_q \odot q^t \tag{4}$$

$$\overrightarrow{u} = q^t \odot v_q \odot q \tag{5}$$

Where $\odot$ denotes the Hamilton product of the quaternion vectors.

B. WEARABLE DEVICE

Wearable technology is a powerful novel tool with a huge potential to disrupt healthcare methods in diagnosis, monitoring and patient treatment. Currently, there is evidence in the scientific literature for a ongoing research effort to design and develop wearable devices that effectively help support clinical practice [8]–[12], [20]–[23].

In this context, the project reported in this paper is part of the experimental results of a wearable platform designed to help physicians monitor heart failure patients. Furthermore, the development may serve as a potent tool to enable remote monitoring from the patient's home, avoiding the inconveniences of hospital care whenever is not necessary. The proposed device is capable of continuous monitoring of the biological impedance of the tissue located in the patient's ankle. This is used as a biomarker to analyze and evaluate the accumulation of leg liquid, which tends to form lower limb aedema in patients with this condition.

Biological impedance analysis serves as a mean to evaluate tissue hydration in the local area where the electrodes are placed. However, this setup is not perfect, and inherent noise arises whenever the patient is moving of the testing conditions are changing (motion artifacts, changes in ankle orientation which may cause device displacement, external body moist, etc.). The authors considered the addition of an Inertial Motion Unit to further analyze and characterize

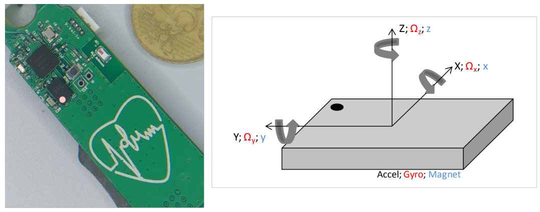

FIGURE 1. Magnetization as a function of applied field. It is good practice to explain the significance of the figure in the caption.

FIGURE 2. Wearable device placed on the ankle and sensing reference frame illustrated.

impedance measurements according to the patient's posture and to keep track of the activity levels in the patients, which, as the scientific literature suggests, may be an important biomarker for monitoring heart failure condition.

Body tracking and activity level estimation must be performed from the data acquired by the IMU device, Bosch BNO055. As we already know, this information is provided in the form of a quaternion, which will serve as a translation method between different reference frames. Figure 1 illustrates the wearable device printed circuit board along with the bosch BNO055 device (highlighted with an orange dot). Next to the board, the sensing reference frame (SRF) is depicted. This reference frame will serve as the basis for defining the vectors we intend to mark as reference for our future analytics method to discern different body postures. A visualization of the entire wearable system placed in a volunteer's ankle is illustrated in Figure 3.

At this point, we have established the mathematical tools which are to be employed and the sensing reference frames. To meet our purpose of evaluating different body postures, we need to define a couple of static vectors, which will be tracked throughout the experimental gathering. An initial method was proposed in [19]. This method aims to track the downward-pointing vector as the unique measurement to analyze body posture. The authors, however, realized that much more information was potentially extracted if that methodology was extended to also track heading pointing vector. These two directions represent, respectively, the direction toward the ground (S_{SRF}) and the foot direction (T_{SRF}) in the sensing reference frame (Fig. 3). From the sensing reference frame the downward pointing vector S_{SRF} and the heading vector T_{SRF} are defined as:

$$\overrightarrow{S_{SRF}} = [0 \quad -1 \quad 0] \tag{6}$$

$$\overrightarrow{T_{SRF}} = [-1 \quad 0 \quad 0] \tag{7}$$

The designed wearable device is Bluetooth low-energy (BLE) enabled and supports data extraction via an Android mobile phone custom application. The application periodically retrieves all available data from the wearable and sends the information to a remote time-series database. The information is then further analyzed locally after all experimental acquisition has been performed.

The microcontroller performs well enough in terms of energy management; however, to achieve the greatest battery life possible, we carefully reviewed all the components included. Impedance sensor provides a fair standby mode, drastically reducing the current consumption, but the IMU sensor did not have a similar feature. In order to further reduce standby power consumption and enable extended operation, we added electronic switches to the IMU sensor device. The final energy characterization was performed using a Nordic Power Profiler Kit II, a potent tool to evaluate the small current drawn by the device while working in all states. The device was designed with the aim of achieving the lowest standby current possible and the value obtained from the tests performed report a total power consumption of $5\mu A$ continuous current draw while in this mode. The device will be in this mode for most of the operating life:

$$I_{standby} = 5\mu A \tag{8}$$

The second step of energy characterization is to evaluate current consumption while performing the acquisition. This device is capable of performing a full acquisition cycle; perform a biological impedance measurement, acquire battery voltage, and obtain motion values in a total of 12 seconds. Using the same Nordic platform, we obtained peak values of up to $15mA$ for this process and a mean value of $12mA$.

$$I_{acq} = 12mA \tag{9}$$

A typical CR2032 coin cell battery usually can hold up to $220mAh$ of power charge. The computation of the estimated battery life with the computed power consumptions reported by the energy characterization tests are described in the following lines. First, we need to estimate mean current consumption over an hour period. This is:

$$I_h = \frac{3520 \cdot 5\mu A + 4 \cdot 20 \cdot 1200\mu A}{3600} = 31,55\mu A \tag{10}$$

With the above averaged value over an hour, we can easily compute the total number of hours per coin cell battery, which will be able to support our device operating in the described measurement protocol.

$$E_{hours} = \frac{220000\mu Ah}{31,55\mu A} = 6973 hours \tag{11}$$

The obtained value of 6973 hours would provide enough running time to perform continuous monitorization of heart failure patients for more than 9 months out of a single coin cell battery. This result is fair enough to provide a long period without having to consider a battery change that disrupts device operation.

C. ACTIVITY AND BODY TRACKING ALGORITHM

The wearable device implements a protocol to optimize battery life and allow extended operation. The acquisition period was established at a 15-minute cadence. The microcontroller and all circuit components are in the lowest power configuration while the measurements are waiting to be acquired, thus guaranteeing extended battery operation and minimizing power consumption. Every 15 minutes, a complete set of measurements is acquired. This set consists of biological impedance measurements and battery and orientation results from the IMU sensor. All measurements are gathered through the BLE interface. After the acquisition, the device is set to establish low power mode again until the next measurement timer expires. This event will reset the cycle, triggering a new measurement. Orientation data acquisition reports the current orientation status in quaternion form. At the same time, the device records an extended inertial measurement period of 5 seconds. This is performed to allow the microcontroller to compute statistics over the quaternions gathered which would enable us to analyze whether there was motion or not in the device (person was walking or moving the ankle). The Inertial sensor has an acquisition period of 100 ms.

The analytical method presented in this project aims to classify the patient's body status into three different categories with respect to the patient's position.

- Laying Down: The patient is in horizontal position, i.e. resting on a bed.
- Sitting: The patient's body is in a sitting position with limited motion.
- Standing/Walking: The patient is in the vertical position, walking or standing.

An initial approach to classifying body posture from acquired attitude measurements would define a region that includes all potential S vector directions. This can be achieved

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by defining an angle with respect to natural down vector and rotating 360º degrees over Z axis, forming a sphere fraction. If the measured vector is contained within this vertical region, then the wearer is considered as in vertical position; if the vector is outside of this region, then the wearer is in horizontal position. With the above protocol established and the position categories estimation method, we aim at further identifying activity levels. The following motion (M_i) metric is defined for such a purpose:

$$M_i = \begin{cases} 1 & \text{if } \theta(T_i - T_{i-1}) \geq T_{THR} \\ 1 & \text{if } var(q) \geq V_{THR} \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

Being M_i an indicator of orientation variation since the last period. Vector T is located in the horizontal plane and will describe the foot direction with respect to the north magnetic pole. T_i represents the current acquisition T vector and T_{i-1} would denote the previous period T vector. T_{THR} denotes an angle variation threshold to discern between the two options. This threshold is the limit above which we consider a heading change large enough to classify the point as a displacement from the previous state. In addition to heading analysis and region classification, the sensor provides a measurement that helps to understand if the device is in motion or static, we will mark the point as dynamic ($M_i = 1$) if the variance of the quaternion is above a certain threshold (V_{THR}).

To evaluate body position and perform classification, we will assume that the wearer is in horizontal position unless a vertical position is found. A patient who wears the device in a vertical position will result in all motion values being set to zero ($M_i = 0$) even if the dynamic threshold is met. This enables the system to discern between horizontal and vertical positions. These distinctions would translate into understanding the patient's body posture and ultimately discern whether is laying down (horizontal) or standing/walking/sitting down, respectively. This initial approach allows us to separate horizontal and vertical postures.

An additional posture classification between standing and sitting potential positions is estimated by observing the evolution of the device heading (direction of the T vector). In this context, a vertical position with activity (either variation across T vector or dynamic captures derived from analyzing the variance of the quaternion) ($M_i = 1$) will be considered as standing/walking, whereas a vertical position with no activity ($M_i = 0$) will be considered as sitting down. We will further evaluate the results for this proposal in a later section of this paper.

Finally, a metric to estimate patient's activity on a daily basis can be provided by defining the following activity index (A_{index}) sum across the whole measurement set for a day:

$$A_{Index} = \sum M_i/n \tag{13}$$

The A_{index} value would range from 0 to 1 and is an indicator of the activity level of the patient in the selected period of time.

D. TESTING AND VALIDATION METHODOLOGY

Initial experimental validation for the method presented was performed recruiting 4 healthy volunteers with an age range of 28-64 years. Informed consent was prepared and signed by all of them. Volunteers were provided with a wearable device and a smartphone. They were asked to wear the device and log and record every possible position in a notebook provided to them. The logs needed to be detailed and accurate in terms of time periods. We asked them to classify their positions in three different groups; namely laying down horizontally, walking/standing and sitting down. The values generated by the volunteers and the wearable device were then analyzed to validate the proposed algorithm estimation results. A total period of two days per volunteer was used for the experimental validation.

The designed wearable device was also tested in a pilot clinical trial at the Hospital Universitario Virgen del Rocío, Seville, Spain. This clinical test allowed us to acquire measurements from several healthy volunteers and patients suffering from Heart Failure, with the objective to verify different behaviour patterns. Continuous monitoring using the wearable device was performed to healthy volunteers and patients for more than 14 days with the system placed in the ankle.

II. RESULTS

A. EXPERIMENTAL VALIDATION

The method parameters, the vertical threshold for horizontal / vertical discrimination, dynamic motion (V_{THR}) and the angle threshold (T_{THR}) employed for performing the position estimation from experimental are described in the following Table 1.

TABLE 1. Algorithm parameters used for the experiment.

Parameter	Value
Vertical Threshold	$1.25 \cdot \frac{\pi}{4}$
Dynamic Motion Threshold (V_{THR})	0.0025
Angle Threshold (T_{THR})	30

A total of 4 healthy volunteers were asked to record their positions over a two-day period. These volunteers would log continuous activity as instructed by the authors who managed the experiment. The focus on information tracking was to adequately log postured corresponding to one of the three potential body positions (Laying down, sitting down and standing/walking). Furthermore, to correctly evaluate the sensing and analytical results against each volunteer record, they time tracked all the positions during the whole experiment. The results for the validation of the method are presented in Table 2.

The Vertical/Horizontal discrimination is scoring 97.6% accuracy, correctly estimating 83 of 85 measurements. The next classified value corresponds to sitting down positions and is correctly determined in 45 of 67 measurements, providing 67.2 % accuracy. Finally, standing / walking position returns an accuracy of 63.5% with 61 out of 96 correct

TABLE 2. Experimental Results from 4 healthy volunteers.

Position	Correct	Measurements	Accuracy (%)
Laying Down	83	85	97,6
Sitting Down	45	67	67,2
Standing / Walking	61	96	63,5

estimates. The overall accuracy calculation provides a 76.2 % accuracy result.

III. DISCUSSION

In this article, we propose a method for body position analysis and motion tracking in patients with heart failure. This method uses measurements from an inertial motion unit implemented in a low power device. The acquisition protocol is established to gather measurements every 15 minutes. Since the paper is focused on body tracking, we are only using attitude measurements in the form of quaternions to perform the estimation of the body positions.

Validation results demonstrate that the method is capable of discerning between horizontal and vertical positions (97.6%), with lower accuracy indices for sitting down and standing/walking determinations. Although the results may be slightly improved by fine tuning the algorithm parameters (see Table 2), there is an implicit complexity in performing a discrimination between sitting down and standing/walking positions from a sensor in the ankle. Furthermore, motion artefacts, even after adjusting the parameters, are a source for determination errors in the proposed method.

A final remark is proposed regarding real data from a healthy volunteer and a heart failure patient in a fortnight period. The acquired measurements and the position estimation were presented to illustrate the severe differences between the two individuals. Monitoring the activity index in combination with volumetric impedance values could provide an additional tool to physicians to monitor and control HF patients.

Future work of this research project includes the incorporation of additional measurements, such as the acquisition of data from the mobile phone, including, but not limited to, GPS, step counters, and phone orientation. This information is not restricted in terms of power and can be an useful tool to further incorporate additional sensor fusion techniques and to better estimate the position of the patient's body. Furthermore, exploration of potential Machine Learning (ML) techniques and algorithms will potentially be able to provide an even better estimation and understanding of the patients postures. This is a natural continuation research work which the authors are already beginning to explore.

Additionally to the work presented in this paper, we provide the following two figures illustrating the proposed algorithm results over an extended period of time. These results illustrate the previously mentioned activity index A_{index}. This index would overlap the Standing/Walking classification, which is described in red on the daily analysis graph. Those two figures presented illustrate a big difference in terms of activity between the two different subjects and also with respect to how much daily time is spent in a horizontal position (laying down).

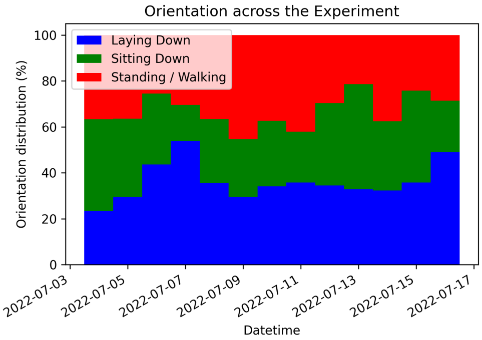

FIGURE 3. Healthy volunteer Body tracking.

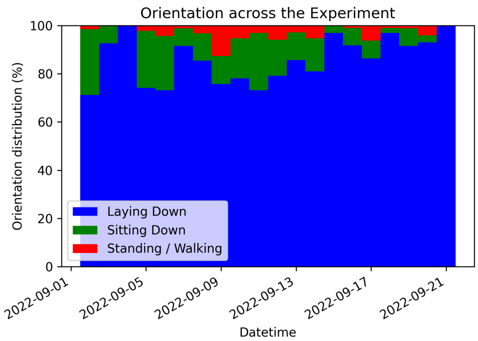

FIGURE 4. Heart Failure Patient, Body tracking.

IV. CONCLUSION

This paper has presented an analytical method for body position analysis and motion tracking, demonstrating encouraging experimental results. The significance of this contribution lies in providing a novel and satisfactory method for discerning the position of a patient laying down from the positions of standing/walking or sitting. Further research is required to be able to monitor additional postures (such as discerning sitting down from standing/walking).

The implications for patients and clinical practice are noteworthy. Tracking and analyzing the position of the patient is essential for interpreting how the liquid accumulation in the patient's leg is evolving. Body tracking may help reduce artifact errors that occur when a measurement is taken whenever the patient is in motion or has recently changed posture. This is happening because impedance electrodes are sensitive to variations in contact levels. Furthermore, this posture traking is relevant to the patient's health status as observed in section III. Research into further improving the results, particularly for standing/walking or sitting positions, is already in progress. Expectation are set for this research to achieve greater significance and extended usage in clinical practice for heart failure disease diagnosis and monitoring.

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REFERENCES

[1] E. E. S. van Riet, A. W. Hoes, K. P. Wagenaar, A. Limburg, M. A. J. Landman, and F. H. Rutten, "Epidemiology of heart failure: the prevalence of heart failure and ventricular dysfunction in older adults over time. A systematic review," European Journal of Heart Failure, vol. 18, no. 3, pp. 242–252, 2016.

[2] P. Ponikowski, A. A. Voors, S. D. Anker, H. Bueno, J. G. Cleland, A. J. Coats, V. Falk, J. R. González-Juanatey, V. P. Harjola, E. A. Jankowska, M. Jessup, C. Linde, P. Nihoyannopoulos, J. T. Parissis, B. Pieske, J. P. Riley, G. M. Rosano, L. M. Ruilope, F. Ruschitzka, F. H. Rutten, P. Van Der Meer, H. S. Sisakian, E. Isayev, A. Kurlianskaya, W. Mullens, M. Tokmakova, P. Agathangelou, V. Melenovsky, H. Wiggers, M. Hassanein, T. Uuetoa, J. Lommi, E. S. Kostovska, Y. Juilliere, A. Aladashvili, A. Luchner, C. Chrysohoou, N. Nyolczas, G. Thorgeirsson, J. M. Weinstein, A. D. Lenarda, N. Aidargaliyeva, G. Bajraktari, M. Beishenkulov, G. Kamzola, T. Abdel-Massih, J. Celutkiene, S. Noppe, A. Cassar, E. Vataman, S. AbirKhalil, P. van Pol, R. Mo, E. Straburzynska-Migaj, C. Fonseca, O. Chioncel, E. Shlyakhto, M. Zavatta, P. Otasevic, E. Goncalvesova, M. Lainscak, B. D. Molina, M. Schaufelberger, T. Suter, M. B. Yılmaz, L. Voronkov, and C. Davies, "2016 ESC Guidelines for the diagnosis and treatment of acute and chronic heart failure," 7 2016.

[3] E. J. Benjamin, S. S. Virani, C. W. Callaway, A. M. Chamberlain, A. R. Chang, S. Cheng, S. E. Chiuve, M. Cushman, F. N. Delling, R. Deo, S. D. de Ferranti, J. F. Ferguson, M. Fornage, C. Gillespie, C. R. Isasi, M. C. Jiménez, L. C. Jordan, S. E. Judd, D. Lackland, J. H. Lichtman, L. Lisabeth, S. Liu, C. T. Longenecker, P. L. Lutsey, J. S. Mackey, D. B. Matchar, K. Matsushita, M. E. Mussolino, K. Nasir, M. O'Flaherty, L. P. Palaniappan, A. Pandey, D. K. Pandey, M. J. Reeves, M. D. Ritchey, C. J. Rodriguez, G. A. Roth, W. D. Rosamond, U. K. A. Sampson, G. M. Satou, S. H. Shah, N. L. Spartano, D. L. Tirschwell, C. W. Tsao, J. H. Voeks, J. Z. Willey, J. T. Wilkins, J. H. Y. Wu, H. M. Alger, S. S. Wong, and P. Muntner, "Heart Disease and Stroke Statistics—2018 Update: A Report From the American Heart Association," Circulation, vol. 137, no. 12, pp. e67–e492, 2018.

[4] F. Braunschweig, M. R. Cowie, and A. Auricchio, "What are the costs of heart failure?," Europace, vol. 13, 5 2011.

[5] E. Rando, P. Perez, S. F. Scagliusi, F. J. Medrano, G. Huertas, and A. Yufera, "A Plethysmography Capacitive Sensor for Real-Time Monitoring of Volume Changes in Acute Heart Failure," IEEE Transactions on Instrumentation and Measurement, vol. 70, 2021.

[6] D. Lindholm, E. Fukaya, N. J. Leeper, and E. Ingelsson, "Bioimpedance and New-Onset Heart Failure: A Longitudinal Study of >500 000 Individuals From the General Population," Journal of the American Heart Association: Cardiovascular and Cerebrovascular Disease, vol. 7, 7 2018.

[7] M. H. G. Monje, G. Foffani, J. Obeso, and A. Sanchez-Ferro, "New Sensor and Wearable Technologies to Aid in the Diagnosis and Treatment Monitoring of Parkinson's Disease," Annual Review of Biomedical Engineering, vol. 21, no. 1, pp. 111–143, 2019.

[8] S. Ancona, F. D. Faraci, E. Khatab, L. Fiorillo, O. Gnarra, T. Nef, C. L. A. Bassetti, and P. Bargiotas, "Wearables in the home-based assessment of abnormal movements in Parkinson's disease: a systematic review of the literature," Journal of Neurology, vol. 269, no. 1, pp. 100–110, 2022.

[9] M. J. Bradshaw, S. Farrow, R. W. Motl, and T. Chitnis, "Wearable biosensors to monitor disability in multiple sclerosis," Neurology: Clinical Practice, vol. 7, p. 354, 8 2017.

[10] B. A. Hickey, T. Chalmers, P. Newton, C.-T. Lin, D. Sibbritt, C. S. McLachlan, R. Clifton-Bligh, J. Morley, and S. Lal, "Smart Devices and Wearable Technologies to Detect and Monitor Mental Health Conditions and Stress: A Systematic Review," Sensors, vol. 21, no. 10, 2021.

[11] B. D. B. Lopez, J. A. A. Aguirre, D. A. R. Coronado, and P. A. Gonzalez, "Wearable technology model to control and monitor hypertension during pregnancy," Iberian Conference on Information Systems and Technologies, CISTI, vol. 2018-June, pp. 1–6, 6 2018.

[12] N. Rens, N. Gandhi, J. Mak, J. Paul, D. Bent, S. Liu, D. Savage, H. Nielsen-Bowles, D. Triggs, G. Ata, J. Talgo, S. Gutierrez, and O. Aalami, "Activity data from wearables as an indicator of functional capacity in patients with cardiovascular disease," PLOS ONE, vol. 16, p. e0247834, 3 2021.

[13] J. Stehlik, C. Schmalfuss, B. Bozkurt, J. Nativi-Nicolau, P. Wohlfahrt, S. Wegerich, K. Rose, R. Ray, R. Schofield, A. Deswal, J. Sekaric, S. Anand, D. Richards, H. Hanson, M. Pipke, and M. Pham, "Circulation: Heart Failure Continuous Wearable Monitoring Analytics Predict Heart Failure Hospitalization The LINK-HF Multicenter Study," 2020.

[14] R. Fisher, A. Smailagic, and G. Sokos, "Monitoring health changes in congestive heart failure patients using wearables and clinical data," Proceedings - 16th IEEE International Conference on Machine Learning and Applications, ICMLA 2017, vol. 2017-December, pp. 1061–1064, 2017.

[15] T. Braun, A. Wiegard, J. Geritz, C. Hansen, K. E. Tan, H. Hildesheim, J. Kudelka, C. Maetzler, J. Welzel, R. Romijnders, W. Maetzler, P. Bergmann, T. Braun, A. Wiegard, J. Geritz, C. Hansen, K. E. Tan, H. Hildesheim, J. Kudelka, C. Maetzler, J. Welzel, R. Romijnders, W. Maetzler, and P. Bergmann, "Association between heart failure severity and mobility in geriatric patients: an in-clinic study with wearable sensors," Journal of Geriatric Cardiology, 2022, Vol. 19, Issue 9, Pages: 660-674, vol. 19, pp. 660–674, 9 2022.

[16] L. Omelina, B. Jansen, B. Bonnechère, M. Oravec, P. Jarmila, and S. van Sint Jan, "Interaction Detection with Depth Sensing and Body Tracking Cameras in Physical Rehabilitation," Methods of information in medicine, vol. 55, no. 1, pp. 70–78, 2016.

[17] "Smart Sensor BNO055 | Bosch Sensortec."

[18] Institute of Electrical and Electronics Engineers., "IEEE standard for inertial systems terminology," p. 30, 2009.

[19] S. J. Fernandez Scagliusi, D. M. Fernandez, P. P. Garcia, G. H. Sanchez, F. J. Medrano Ortega, and A. Y. Garcia, "A low power approach to body position estimation for HF patient monitoring by an ankle positioned Inertial Measurement Unit (IMU)," 2022 37th Conference on Design of Circuits and Integrated Circuits (DCIS), pp. 01–06, 11 2022.

[20] C. Ferguson, L. D. Hickman, S. Turkmani, P. Breen, G. Gargiulo, and S. C. Inglis, ""Wearables only work on patients that wear them": Barriers and facilitators to the adoption of wearable cardiac monitoring technologies," Cardiovascular Digital Health Journal, vol. 2, no. 2, pp. 137–147, 2021.

[21] S. Lee, G. Squillace, C. Smeets, M. Vandecasteele, L. Grieten, R. De Francisco, and C. Van Hoof, "Congestive heart failure patient monitoring using wearable Bio-impedance sensor technology," in Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS, vol. 2015-November, pp. 438–441, Institute of Electrical and Electronics Engineers Inc., 11 2015.

[22] E. Rodríguez-Villegas, G. Chen, J. Radcliffe, and J. Duncan, "A pilot study of a wearable apnoea detection device.," BMJ open, vol. 4, p. e005299, 10 2014.

[23] M. Menolotto, S. Rossi, P. Dario, and L. Della Torre, "Towards the development of a wearable Electrical Impedance Tomography system: A study about the suitability of a low power bioimpedance front-end," in 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp. 3133–3136, IEEE, 8 2015.

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