UNIVERSITÀ POLITECNICA DELLE MARCHE

FACOLTÀ DI INGEGNERIA

Corso di Laurea Magistrale in Biomedical Engineering

REVIEW ON WEARABLE AND PORTABLE SENSORS FOR RECORDING OF CARDIAC SIGNALS WHILE PRACTICING SPORT

REVIEW SU SENSORI INDOSSABILI E PORTATILI PER L'ACQUISIZIONE DI SEGNALI CARDIACI DURANTE LO SPORT

Relatore:

Prof.ssa Laura Burattini

Tesi di Laurea di:

Francesca Ripanti

Anno Accademico 2021/2022

ABSTRACT

Wearable and portable devices, capable to acquire cardiac signals, are becoming increasingly popular for monitoring physiological parameters while practicing sport given the advance in miniaturized technologies and powerful data and signal processing applications. These measures are increasingly used to monitor athletes' performances and risk indices for sport related sudden cardiac death. The purpose of this review was to investigate commercially wearable and portable devices employed for cardiac signals monitoring during sport activity. Systematic search of literature have been conducted on PubMed, Scopus and Web of Science. After study selection, a total of 37 studies were included in the review. The studies were categorized based on the application of the wearable or portable devices in validation studies, clinical studies and development of algorithms and databases.

From the analysis of all the 37 studies, it was found that the most recurring device brand was Polar while the most analysed sport was running. Results from clinical studies highlighted that wearable technologies are crucial to improve athletes' performance and reduce the risk of adverse cardiovascular events. At the same time, the need for standardized validation of these technologies emerged. Indeed, results obtained from the validation studies turned out to be heterogeny and scarcely comparable, since the metrological characteristics reported were different. Moreover, the validation of the several devices has been carried out during different sport activities. As for regard algorithms and database category, only one study focused on the implementation of a database instead all the other studies focused on the development of a specific signal processing algorithm using data recorded from the wearable devices.

Index

INTRODUCTION

Over the years, wearable devices have become increasingly popular as they are relatively inexpensive and user-friendly. The technology related to wearable devices has become more and more advanced and will continue to advance due to the miniaturization of electronic components. Such devices are designed to be worn at different location on the human body (e.g. wrist and chest) for non-invasive sensing of an individual's parameters without interrupting or restricting the user's movements. Heart rate (HR), skin temperature, steps, and energy expenditure are just a few of the many parameters of physical activity that can be tracked.

The applicability of wearable devices has expanded over the years to various fields. Currently, due to the many benefits of collecting a lot of data on the device, wearable technology has invaded the world of sports. Information gathered from these devices enables individual athletes and sport teams, to maximize performance and minimize injuries. Coaches on the other hand, thanks to the real-time monitoring can refine the quality of training and improve the physical and psychological fitness of their players.

Although athletes are considered very fit and healthy, intense exercise can potentially increase the risk of arrhythmias and, in rare cases, sudden cardiac death (SCD) that is one of the leading causes of death during sport activities. Symptoms appear rarely and in specific situations during high-intensity exercise where conventional monitors are impractical. HR tracking is a cheap and non-invasive tool for cardiovascular monitoring through wearable sensors while playing sport. Depending on the technology of the commercial wearable or portable device used, HR is derived from the time intervals among consecutive heart beats in the electrocardiogram (ECG) or among consecutive pulsations in the photopletysmogram (PPG)

Advances in wearable technology during sports activity have led researchers to direct themselves toward this topic and that is why actually, numerous research on that are available. At the best of our knowledge, there is no review reporting portable and wearable devices capable of acquiring cardiac signals during sport. So, this study was designed with the purpose of summarizing commercially available wearable devices that record cardiac signals, electrocardiogram and heart rate, during sports activity.

1 ANATOMY AND PHYSIOLOGY OF THE CARDIOVASCULAR SYSTEM

1.1 Heart structure

The heart is a vital body organ and is the center of the circulatory system in that it enables the circulation of blood in the body, through its involuntary rhythmic contractions, through blood vessels that are divided into: arteries, veins and capillaries [1,2].

The heart is a muscular organ characterized by a conical pyramidal shape, in fact it has an apex, a base, an anterior or sterno-costal face and a posterior or diaphragmatic face. The base faces posteriorly upward and to the right while the apex faces downward and to the left anteriorly. Generally, in an adult male, the heart has an average length of 12 cm from the base to the apex, a diameter of 8-9 cm transversely and a thickness of 6 cm, finally its weight is about 280-340 g. It is placed obliquely in the thorax, about one third of it is located to the right of the median plane and about two thirds to the left of it.

The heart inside is divided into two separate pumping systems: the right side and the left side (Fig. 1.1). The right side is called the "right heart" and is composed of the right atrium and the right ventricle. The left side is called the "left heart" and is composed of the left atrium and the left ventricle.

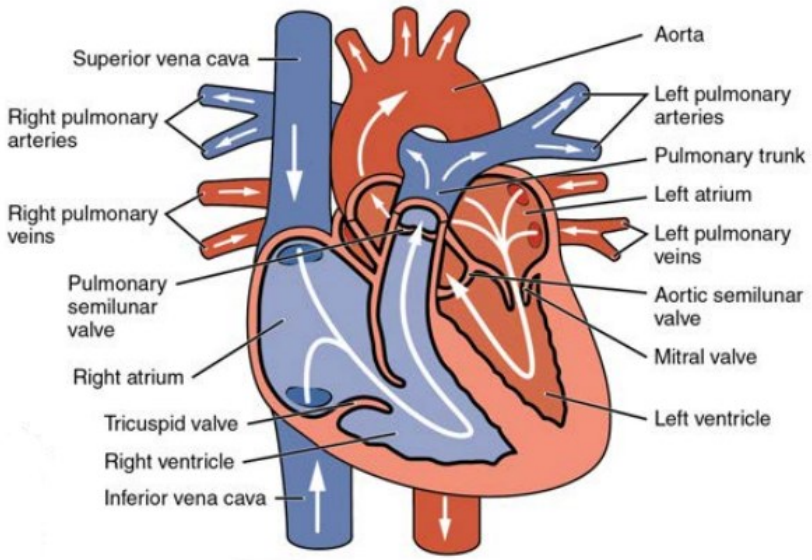


Fig. 1.1 – Anatomy of the heart [3].

The two upper cavities, the atria, communicate with the ventricles below through the two atrioventricular orifices. The right one has a valve called the tricuspid valve while the left one has a valve called the bicuspid valve; these valves ensure unidirectional blood flow from the atria to the ventricles. In contrast, the two atria and the two ventricles are not communicating as they are separated by the interatrial septum and the interventricular septum, respectively.

In addition, the heart communicates with the blood vessels through two valves: the aortic valve and the pulmonary valve. These valves are known generically as semilunar valves because of their shape and are responsible for controlling the direction of flow out of the heart.

The heart and adjacent portions of the major vessels are enveloped by a large sac called the pericardium, which is divided into fibrous and serous pericardium [2].

The fibrous pericardium, which goes to make up the outer part of the sac, consists of dense fibrous connective tissue while the inner part identifies the serous pericardium. The latter being a serous membrane is composed of a parietal leaflet that lines the inner surface of the fibrous pericardium and a visceral leaflet that adheres to the heart forming the outer lining called the epicardium. These two membranes are separated by a pericardial cavity in which there is pericardial fluid that allows the heart some freedom of movement.

The heart wall is composed of three overlapping layers that from the outside to the inside are the epicardium, myocardium, and endocardium. The epicardium as already mentioned is the visceral leaflet of the serous pericardium which adheres externally to the myocardium. The endocardium, on the other hand, is a membrane that lines the internal cavities of the heart [1].

The myocardium, which forms the actual structure of the heart wall, exhibits a muscular nature, being composed of striated muscle tissue. It is divided into common myocardium consisting of myocardiocytes that have the ability to contract and specific myocardium consisting of specialized cells that have the ability to generate and conduct an impulse. Its thickness is different in each cavity as it depends on the contractile force each of them has to exert, which is why the wall of the atria is thinner than the wall of the ventricles, which on the other hand is thicker and more robust.

1.2 Conduction system of the heart

The conduction system of the heart (Fig. 1.2) is that system that generates and conducts the sinus impulse; it consists of the following main structures: the sinoatrial node, the atrioventricular node, the atrioventricular bundle with its left and right branches, and the Purkinje fiber plexus [2].

Cardiac muscle cells are distinguished from others by the property of spontaneous contraction and release. Atrial cells contract and release at a higher rate than ventricular cells.

Cardiac electrical activity originates in the sinoatrial node also called the Keith and Flack node.

The sinoatrial node is an elliptical structure, 3 mm wide, 15 mm long and 1 mm thick, comprising a cluster of specific myocardial cells located in the upper wall of the right atrium near the outlet of the superior vena cava. The cells that make up the sinoatrial node represent the heart's "pace marker," as they dictate the heart's rhythm. The discharge rate of the SA node is 70-80 bpm [4].

The impulse propagates first along the specific myocardial cell bundles that extend from the sinoatrial node into the common myocardium in the atrial walls, causing the two atria to contract simultaneously, and then to the internodal bundles that transmit the stimuli to the atrioventricular node, where the transmitted impulse undergoes a delay of about 40 ms. Propagation is slowed to allow the atria to complete their contraction before contraction of the ventricles occurs.

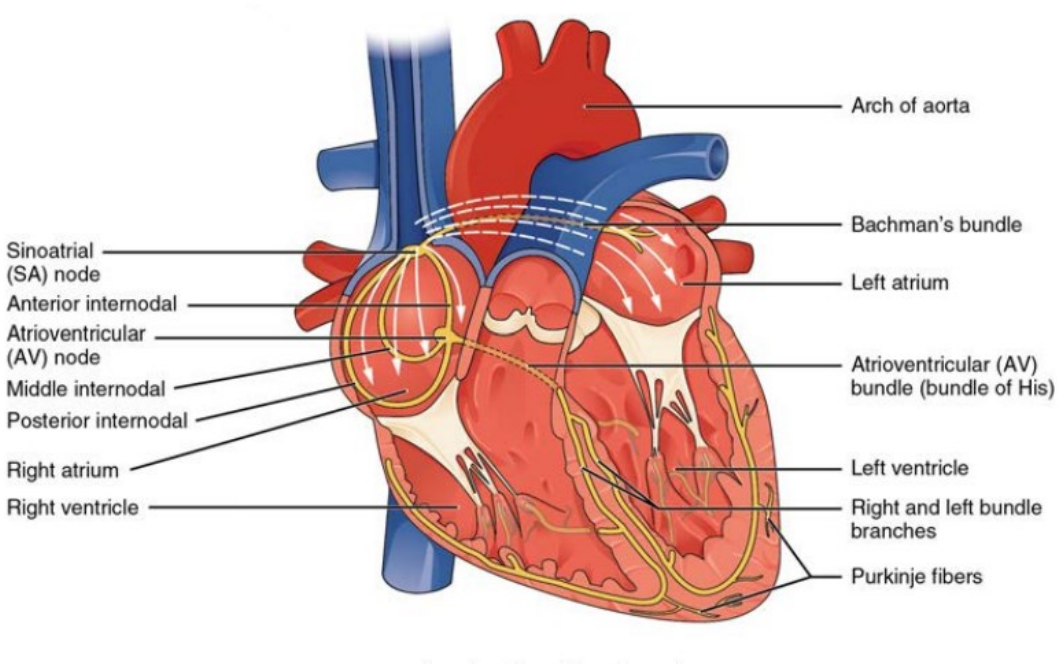


Fig. 1.2 – Conduction system of the heart [3].

The semioval-shaped atrioventricular node comprises a clump of specialized myocardial conductive cells located in the medial wall of the right atrium near the coronary sinus. From it originates the bundle of His or common trunk, which crosses the atrioventricular septum and bifurcates into two branches: the right and left branches, each branch descending toward the apex of the heart terminating in the papillary muscles. At the base of the papillary muscles, the branches also resolve into a series of small bundles that intertwine with each other and ascend toward the base of the ventricles, forming Purkinje networks. AV node fibers can discharge at a frequency of 40-60 bpm and Purkinje fibers can discharge at a frequency of 15-40 bpm [4].

1.3 Action potential of cardiac cells

The heart has the characteristic of being composed of two systems: one capable of generating and conducting electrical activity called the conduction myocardium or specific myocardium and one that instead is capable of responding to stimulation by contracting called the common myocardium [5].

The intracellular environment and the extracellular environment are separated by the cell membrane, and because these, are at different ionic concentrations, a potential difference exists between the inside and the outside called the resting membrane potential. The resting membrane potential of pacemaker cells varies between -60mV and the threshold value, while that of contractile cells is stable at -90mV.

For these reasons, when we talk about the action potential of the heart, we refer to two tracings (Fig. 1.3).

The blue tracing represents the specific myocardial action potential consisting of cells capable of creating and conducting the impulse. The phases of the potential are as follows:

- Phase 4. In this phase, the channels are permeable to Na+, which tends to enter the intracellular environment, and partly to K+, which tends to leak out. Because the electrochemical gradient of Na+ is greater than that of K+ a slow depolarization of the membrane occurs. The increase in depolarization causes some Ca2+ channels to open, as calcium ions enter, the membrane potential gradually tends to the threshold value.
- Phase 0. Upon reaching the threshold value, the entry of calcium ions increases resulting in the peak of the action potential.

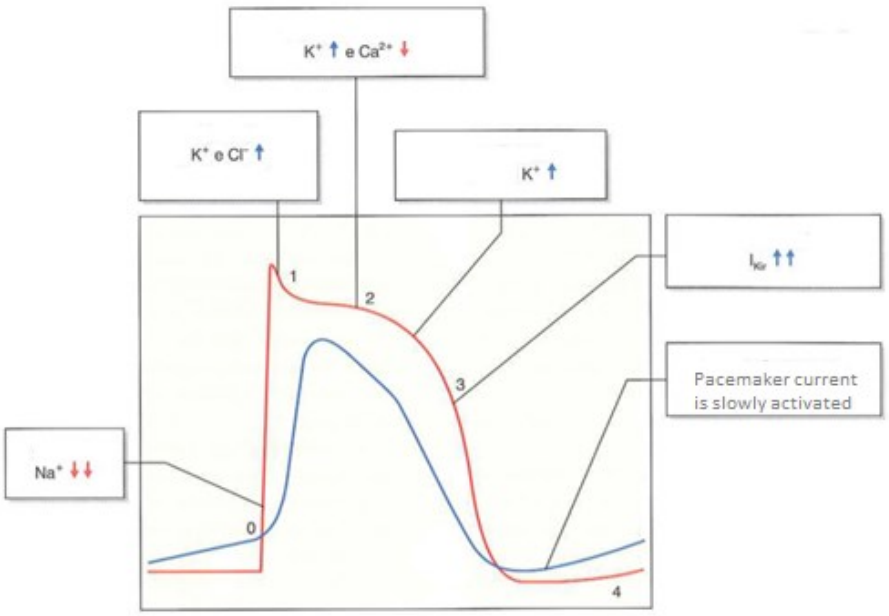


Fig. 1.3 – Phases of the action potential [5].

- Phase 3. Repolarization begins with the closure of calcium channels and maximal activation of potassium channels, resulting in the release of K+ ions.

The red tracing represents the common myocardial action potential and consists of the following five phases:

- Phase 0, rapid depolarization, is caused by the opening of voltage-dependent Na+ sodium channels, which allow sodium ions to flow into the cell interior.
- Phase 1, early partial repolarization, is characterized by the process of inactivation of Na+ channels due to membrane depolarization and the opening of transient K+ potassium output channels, i.e., which are activated and go into refractoriness very rapidly.
- Phase 2, plateau, is called plateau because it is a phase with no change in transmembrane potential, in fact the entry of Ca++ ions are counterbalanced by the exit of K+ ions from the cell. The potential remains stable.
- Phase 3, repolarization, relies on inactivation of calcium channels and persistence of slow potassium current, in fact, Ca++ ion entry is reduced while K+ ions continue to exit the cell.
- Phase 4, resting phase, is the last stage in which resting conditions are restored.

1.4 Cardiac cycle

The cardiac cycle consists of two successive periods: the diastole, period of relaxation of the heart muscle and the systole, period of contraction of the heart muscle. The duration of a cycle is the reciprocal of the heart rate (HR), in fact when the HR increases, the duration of each cycle decreases [4].

The heart is considered a double pump, so all events that occur in the left side are recorded in the right side (Fig. 1.4).

Ventricular diastole begins with closure of the semilunar valves and a subsequent isovolumic release of the ventricles. Ventricular pressure decreases until it becomes less than intra atrial pressure, causing the atrioventricular valves to open. The period of rapid filling begins in which 80% of the blood flows from the atria to the ventricles passively. Then in the phase called diastasis, there is direct passage from the pulmonary veins (left heart) and hollow veins (right heart) to the ventricles of a small amount of blood, about 5%.

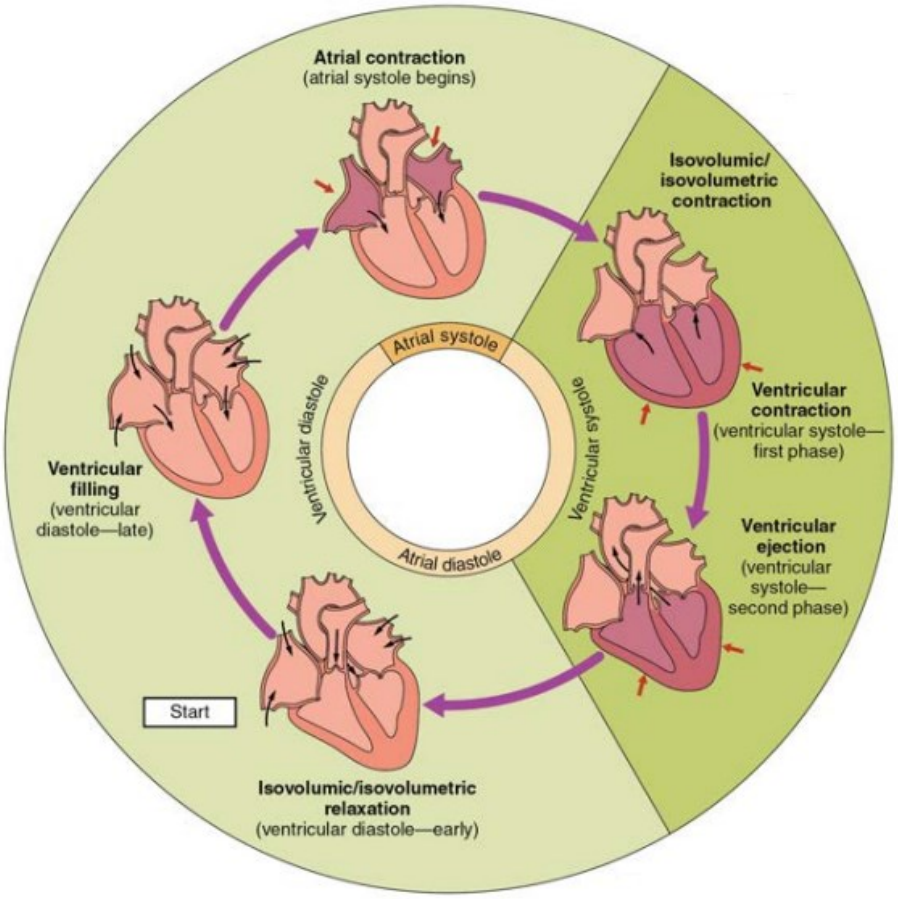


Fig. 1.4 – Overview of the cardiac cycle [3].

At this point, atrial systole begins in which the atria contract, allowing the ventricles to finally fill. The value of intraventricular pressure increases until it exceeds that of intra atrial pressure causing the atrioventricular valves to close. After two hundredths of a second, the intraventricular pressure exceeds the arterial pressure, resulting in the opening of the semilunar valves and the subsequent passage of blood from the left ventricle to the aorta and from the right ventricle to the pulmonary artery. In the first, maximal ejection phase, 70 percent of blood is expelled while the remaining 30 percent in the reduced ejection phase. Arterial pressure becomes greater than intraventricular pressure, so blood tends to flow back from the arteries into the ventricles causing the semilunar valves to close. The atrioventricular and semilunar valves are closed and under these conditions the heart is ready for a new cardiac cycle.

1.5 Circulatory system

The heart is the organ that enables the circulation of blood through arteries, veins and capillaries to the entire body. Arteries are responsible for transporting blood from the heart to the tissues and organs of the human body thus following the centrifugal direction. Capillaries, on the other hand, are the smaller vessels that allow exchanges of water, nutrients, hormones and other substances between the blood and the interstitial fluid. Finally, veins transport waste blood from the periphery to the heart [4].

The circulation (Fig.1.5) is divided into the systemic circulation also called the great circulation and the pulmonary circulation also called the small circulation. The great circulation originates in the left ventricle of the heart, which, by contracting, pushes blood into the aorta artery, which distributes arterial blood to the body via smaller and smaller arteries. These arteries resolve into capillary vessels, where arterial blood, through exchanges with interstitial fluids, gives up oxygen and is charged with carbon dioxide, transforming into venous blood. From the capillaries it proceeds to the venules, which meet and give rise to the veins. Blood from the superior vena cava and the inferior vena cava, returns to the right atrium. The right atrium by contracting pushes blood to the right ventricle. Here is the end of the great circulation and the beginning of the small circulation. The carbon dioxide-rich venous blood through the pulmonary artery and its bifurcations from the right ventricle reaches the lungs. Within these the pulmonary artery resolves into capillaries, in

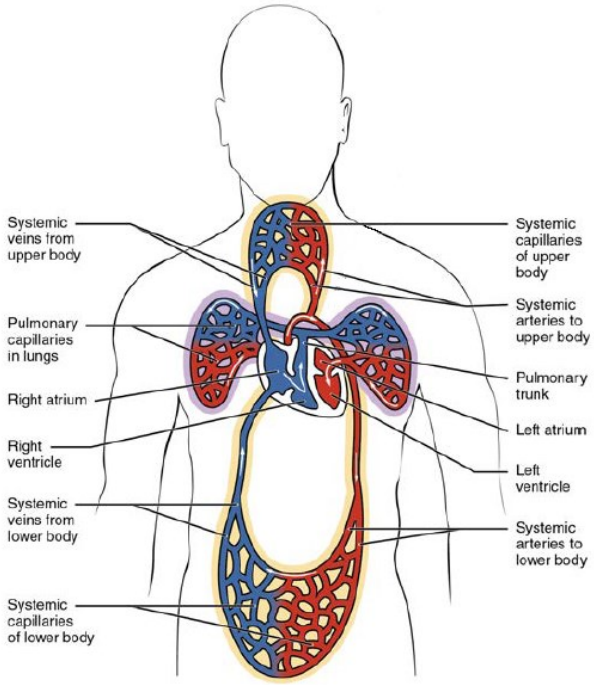


Fig. 1.5 – Circulatory system[3].

which venous blood loses carbon dioxide, gains oxygen and becomes arterial blood. Arterial blood returns to the heart with the four pulmonary veins that flow into the left atrium, where the pulmonary circulation ends [1].

2 CARDIOVASCULAR SIGNALS

2.1 ELECTROCARDIOGRAM

The continuous process of depolarization and repolarization of cardiac cells is the source of electric fields. These emerge toward the surface of the human body due to the ionic, thus conductive, nature of the fluids in the body. The distribution of electric fields on the surface of the human body is manifested by equipotential lines, that are, lines along which the electric potential is constant. Therefore, if two electrodes are placed on the surface of the chest in regions of different potential, it is possible to detect a potential difference, which varies because of the electrical activity of the heart. The recording over time of the heart's electrical activity is called an electrocardiogram (ECG) [6].

The ECG does not record the electrical activity of each individual cell. In fact, for the purpose of simplifying the description of the electric fields generated by the heart muscle, it is possible to consider the entire myocardium as a single electric dipole. This dipole is called the electric dipole of the heart and is described by a positive charge, a negative charge, the distance between the two charges, and the dipole axis. The latter is the direction of the line joining the two charges and can be represented by a vector H, called the instantaneous electrical axis of the heart, which describes the cardiac electrical activity as a whole [6].

2.1.1 Method of acquisition

At least two electrodes, i.e., conductors capable of detecting a potential difference (ddp) when placed in non-equipotential locations, must be used to record the electrocardiographic trace. On the surface of the body, potential differences vary over time and depend on where the electrodes are placed. In order to make electrocardiograms performed on different individuals or at different times on the same individual comparable, it is essential that the positions where the electrodes are placed are standardized. Such predefined electrode positions are called leads [6].

Specifically, leads can be of two types: bipolar and unipolar. Bipolar leads record the potential difference between two electrodes placed in different areas of the body; unipolar leads detect the potential of one part of the body relative to a reference potential.

2.1.1.1 Standard limb leads

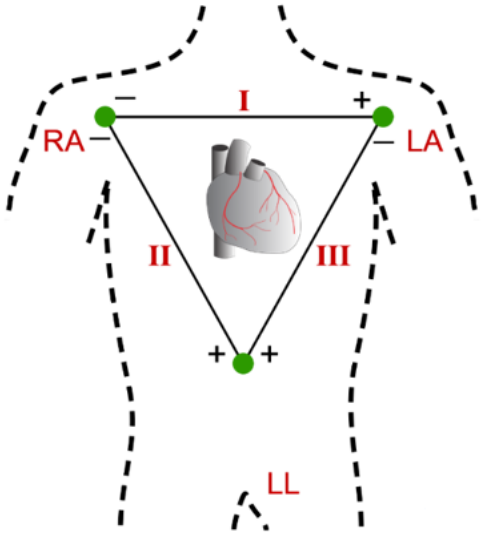
The first electrode arrangement was defined by physiologist Willem Einthoven at the beginning of the last century and is still used today (Fig. 2.1). It involves placing three electrodes at the vertices of an equilateral triangle in the frontal plane. The vertices identified with RA, LA, LL, correspond to right arm, left arm and left leg and constitute the nodes of a closed mesh, so it is possible to apply Kirchhoff's second law, which states that in a closed mesh the sum of potential differences (ddp) must equal zero [6,7,8].

So, knowing the value of two leads, it is possible to determine the value of the third lead.

Each bipolar lead is recorded using two electrodes, one positive type and one negative type.

Specifically:

- the ddp measured between RA and LA and that is $V_{LA} - V_{RA} = V_I$, takes the designation of I derivation, in which the negative terminal is connected to the right arm and the positive terminal to the left arm.
- the ddp measured between RA and LL and that is $V_{LL} - V_{RA} = V_{II}$, takes the designation of II derivation, in which the negative terminal is connected to the right arm and the positive terminal to the left leg.
- the ddp measured between LA and LL and that is $V_{LL} - V_{LA} = V_{III}$, takes the designation of III derivation, in which the negative terminal is connected to the left arm and the positive terminal to the left leg.



2.1-Electrodes disposition for the original leads.

with $V_i = H \cdot a_i$and $= I, II, III$, where a_I, a_{II}, a_{III} are the three verses respectively of the straight lines joining RA with LA, RA with LL, and LA with LL.

The position of the electrodes is standardized, and each electrode is assigned a colour: in the European system RA is red, LA is yellow, and LL is green while in the US system RA is white, LA is black, and LL is red.

2.1.1.2 Augmented leads

Augmented leads devised by Dr. Emanuel Goldberger are also called unipolar limb leads. As with the basic leads, the electrode arrangement is according to the Einthoven triangle, and the plane on which the leads lie is the frontal plane. The set of leads formed by aV_F (Augmented Voltage of the left Foot), aV_R (Augmented Voltage of the right arm) and a aV_L (Augmented Voltage of the left arm), has the characteristic of detecting the potential of one electrode with respect to a reference point formed by the other two electrodes that together form the negative terminal, e.g. the lead aV_F, uses the left foot electrode as the positive and both arm electrodes as the common (negative) link.

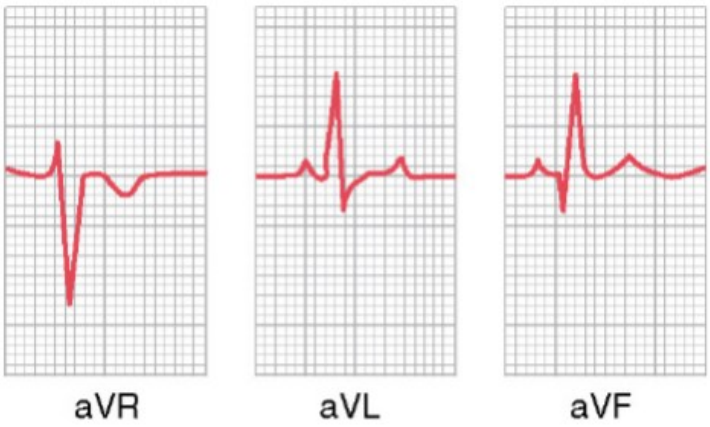
Figure 2.2 shows some recordings from augmented unipolar limb leads.

Augmented leads are related to fundamental leads by the following relationships [6].

$$aV_R = -\frac{1}{2}(I + II) \quad (1)$$

$$aV_L = -\frac{1}{2}(I - III) \quad (2)$$

$$aV_f = \frac{1}{2}(II + III) \quad (3)$$



2.2- Normal electrocardiograms recorded from the three unipolar augmented limb leads [7].

2.1.1.3 Precordial leads

Precordial leads lie in the transverse plane, perpendicular to the plane of the frontal leads. The precordial leads have been introduced for greater definition of cardiac activity; in fact, electrodes are placed at specific sites in the chest therefore particularly close to the cardiac area [6,8]. V1, V2, V3, V4, V5, V6 are the potentials corresponding to the six electrodes and the anatomical sites where they are placed are as follows:

V1: fourth intercostal space to the right of the sternal margin

V2: fourth intercostal space to the left of the sternal margin

V3: halfway between V2 and V4

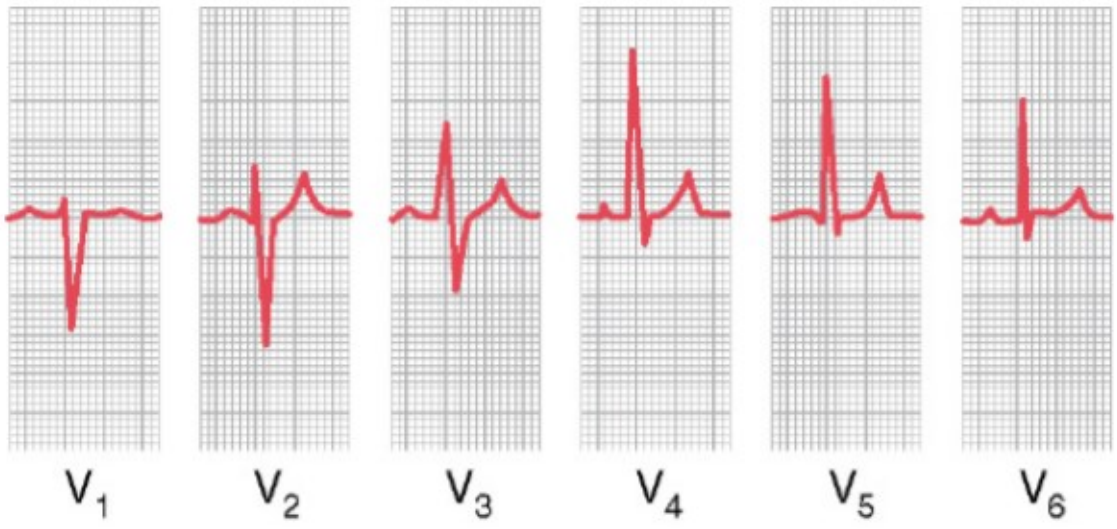
V4: in the fifth intercostal space

V5: halfway between V4 and V6

V6: aligned externally with V4 and V5.

They are all positive electrodes; in fact, they are referred to as unipolar precordial leads, referring to one electrical center, the terminal center of Wilson. Wilson's terminal center is the point created by connecting the electrodes of the three limb leads via a resistor to a common node.

Figure 2.3 shows the ECG tracings of a healthy heart recorded from the six precordial leads.



2.3- Normal electrocardiograms recorded in the six standard precordial leads [2].

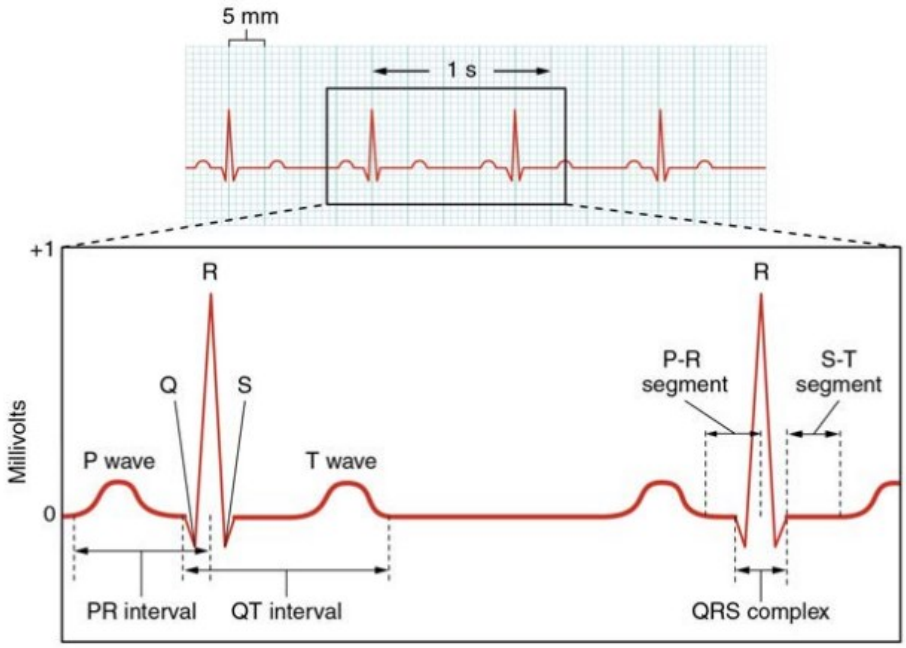
2.1.2 Electrocardiographic signal

A normal electrocardiographic tracing consists of a P wave, a QRS complex and a T wave. The QRS complex in turn consists of three waves: the Q wave, the R wave and the S wave (Fig. 2.4) [7].

The tracing is recorded on a graph paper. On the x-axis, we find the time in seconds, which is related to the speed at which the paper is scrolled. Normally the paper, on which the electrocardiogram is recorded, flows at a speed of 25 mm/s. in which each mm corresponds to 40 ms. There is also the possibility of sliding the paper at 50 and 10 mm/s, with each mm corresponding to 20 and 100 ms, respectively.

On the y-axis, we find the voltages represented in mV. Normally, the calibration in which 1 mV corresponds to a deflection of 10 mm is used. But when the signals are much larger you can select the half calibration, in which 1 mV corresponds to a deflection of 5 mm or conversely, they are very small you can select the double calibration, in which 1 mV corresponds to a deflection of 20 mm.

The first wave of the electrocardiographic trace is the P wave and corresponds to atrial depolarization. The depolarization wave originates from the sinoatrial node and propagates into the atria causing them to contract simultaneously. Blood due to the contraction flows from the upper cavities into the ventricles by passing through the atrioventricular valves.



2.4- A normal tracing shows the P wave, QRS complex, and T wave. Also indicated are the PR, QT, QRS, and ST intervals, plus the P-R and S-T segments [3].

By the time the depolarization wave reaches the atrioventricular node, there is a slowdown necessary to complete the filling of the ventricles. After slowly traversing the AV node, the stimulus proceeds rapidly along the His bundles and finally reaches after traversing the two branches of the conduction system, the endings of the Purkinje fibers, which allow the impulse to spread to the entire ventricular muscle mass. Depolarization of the entire ventricular myocardium produces the QRS complex. Thus, the QRS complex corresponds to ventricular depolarization and subsequent contraction.

The T wave, on the other hand, represents repolarization of the ventricles [8].

The P-Q or P-R interval, in the case where the Q wave is absent, is the time period between the onset of excitation of the atria and the onset of excitation of the ventricles. Its duration is about 0.16 s.

The Q-T interval is the period concerning the contraction of the ventricle, its duration varies as the HR varies but is usually about 0.35 s [7].

2.2 PHOTOPLETHYSMOGRAM

In New Jersey and Stanford in the early 1936, two independent research groups explored the use of a non-invasive optical instrument to assess blood volume changes in rabbit ears.

However, the pioneer of the PPG technique was Alrick Hertzman's team from St. Louis, USA, who a year later published the first study on the use of PPG to measure blood volume changes in human fingers. The word “photoplethysmography” was adopted to etymologically refer to a new technique that could measure volume changes (plethysmography) by optical means (photo).

For several decades PPG technology was limited to physiological studies, kept away from clinical practices. The fact that bulky light sources and sophisticated processing-visualization means were needed to acquire and interpret the PPG signals limited wider regular use.

It was not until the release of light-emitting diode (LED) technology in 1962 that PPG techniques sparked enthusiasm for new research. In particular, the introduction of PPG into clinical routine was undeniably triggered by the development of a so-called pulse oximeter in 1972 by a team of engineers at Nihon Kohden Laboratories.

The introduction of pulse oximetry in clinical routine is undoubtedly associated with the widespread of PPG as a low cost, non-invasive, easy to use monitoring technique [9].

Nowadays PPG is a simple optical technique that uses a light source and a photodetector to detect the volumetric variations of blood circulation. It is a low-cost and non-invasive method that makes measurements at the surface of the skin [10][11].

When the tissue is illuminated by the source, three things will happen depending on the volume of the blood in the tissue: certain amount of the light will be absorbed, certain amount of the light will be transmitted, and certain amount of light will be reflected [12] [13].

In light-tissue interactions, the wavelength of optical radiation is a key factor. Water, the main component of tissues, strongly absorbs light in the ultraviolet and the longer infrared wavelengths. The shorter wavelengths of light are also strongly absorbed by melanin. However, there is a window in the absorption spectrum of water that allows visible (red) and near infrared light to pass more easily, thus facilitating the measurement of blood flow or volume at these wavelengths. Therefore, red or near infrared wavelengths are often chosen for the PPG light source. The depth to which light penetrates the tissue for a given intensity of optical radiation depends on the operating wavelength [10].

2.2.1 Method of acquisition

The typical PPG device contains only few opto-electronic components: a light source and a photodetector. The light source that usually is a LED illuminates the skin and the photodetector measures the reflected light form the tissue. The reflected light is proportional to blood volume variations [11].

There are two main PPG configurations(Fig. 2.5): the transmission mode and reflectance mode. In the transmission ('trans-illumination') mode the tissue sample is placed between the source and detector, instead in the reflection ('adjacent') mode the LED and detector are placed on the same side of the tissue [10].

The traditional mode, that is the transmission one, in order to be effective, has to be used only in thin body sites such as fingertip or earlobe instead the reflection mode may be employed in wrist or forearm [10].

LEDs convert electrical energy into light energy and have a narrow single bandwidth (typically 50 nm). They are compact, have a very long operating life (>105 h), operate over a wide temperature range with small shifts in the peak-emitted wavelength and are mechanically robust and reliable.

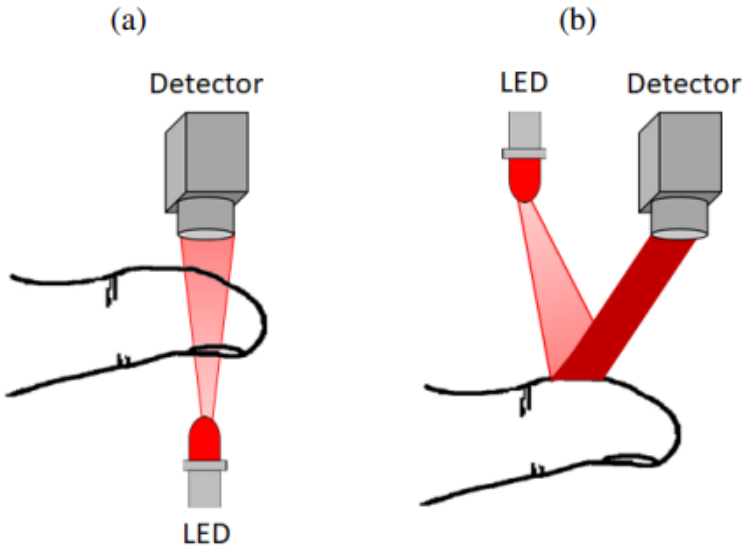


Fig.2.5 Schematic of functioning principles of photoplethysmography sensors:

a) light transmission and b) light reflection [14].

The averaged intensity of the LED should be constant and preferably be sufficiently low to minimize excessive local tissue heating and also reduce the risk of a non-ionizing radiation hazard.

The choice of photodetector is also important (Weinman and Fine 1972, Fine and Weinman 1973). Its spectral characteristics are chosen to match that of the light source. A photodetector converts light energy into an electrical current. They are compact, low-cost, sensitive, and have fast response times. The photodetector connects to low noise electronic circuitry that includes a transimpedance amplifier and filtering circuitry.

Carefully chosen filtering circuitry is also needed to remove the unwanted higher frequency noise such as electrical pick up from (50 Hz) mains electricity frequency interference. Figure 2.6 (a) shows a transimpedance (current-to-voltage) amplifier that converts light intensity at the photodiode (PD) to an amplifier output voltage ($V = I \times R$, transimpedance gain proportional to feedback resistor value R) and figure 2.6 (b) shows the signal conditioning stages surrounding the transimpedance amplifier, which include low pass filtering, high pass filtering and further amplification, signal inversion and signal interface [10].

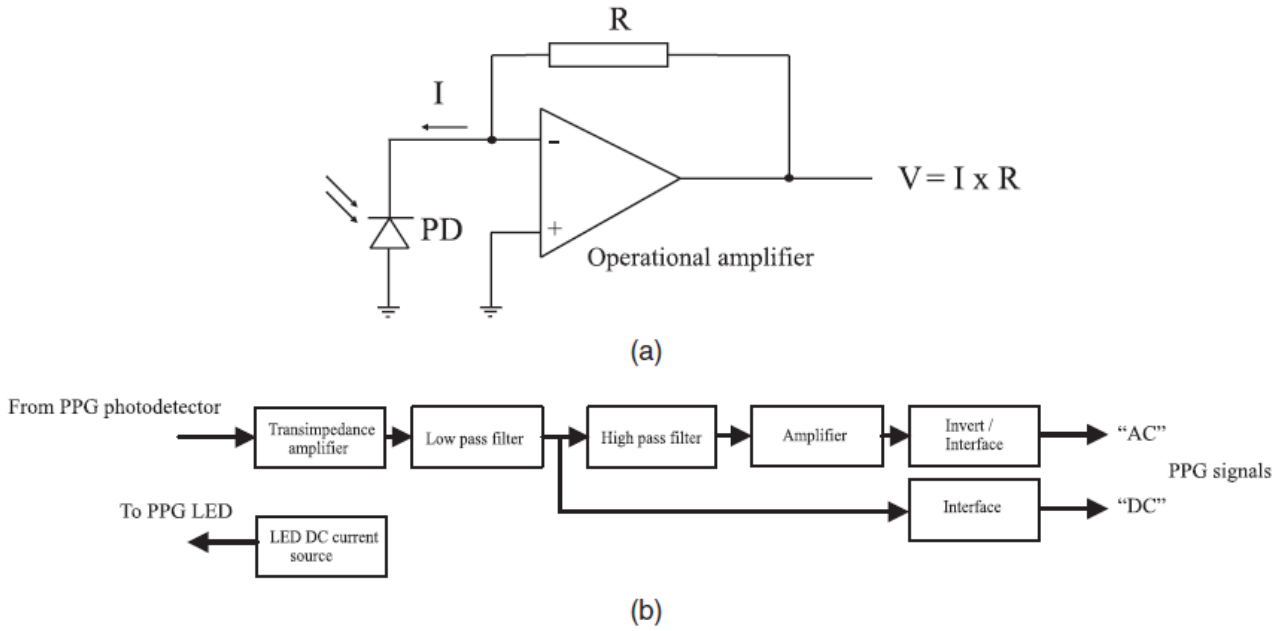


Fig.2.6 Electronic building blocks used in a typical PPG measurement system.
(a) A transimpedance amplifier stage
(b) The signal conditioning stages surrounding the transimpedance amplifier [10].

2.2.2 Photopletismographic signal

The PPG waveform (Fig.2.7) comprises a pulsatile AC component, attributed to cardiac synchronous changes in the blood volume with each heartbeat and a slow varying DC component which depends on respiration, sympathetic nervous system activity and thermoregulation [10].

Each PPG signal comprises two phases: a fast-rising part called anacrotic phase, and a subsequent falling part called catacrotic phase [11].

The anacrotic phase reflects the stretching of blood vessel walls under the increased blood pressure after each heartbeat; the catacrotic phase concerns with the relaxation process of the blood vessel walls in between every two heartbeats [15].

The main characteristics of the PPG waveform are illustrated in figure. 2.8. The systolic phase starts with a valley that marks the pulse wave begin (PWB) and ends with the pulse wave systolic peak (PWSP). The pulse wave end (PWE) is marked by another valley at the end of the diastolic phase. If present, a local maximum or inflection point between PWSP and PWE marks the pulse wave diastolic peak (PWDP). The vertical amplitude distance between PWB and PWSP is the pulse wave amplitude(PWA) and the horizontal distance between PWB and PWE is the pulse wave duration (PWD) [16] [17].

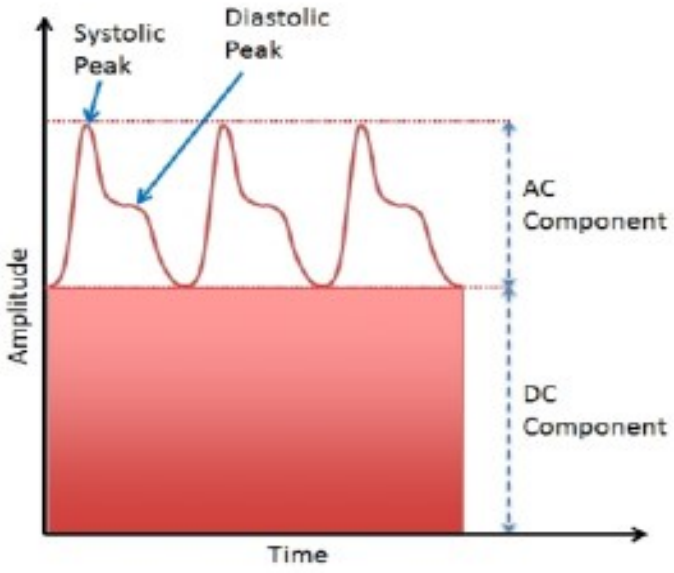


Fig. 2.7 PPG signal [12].

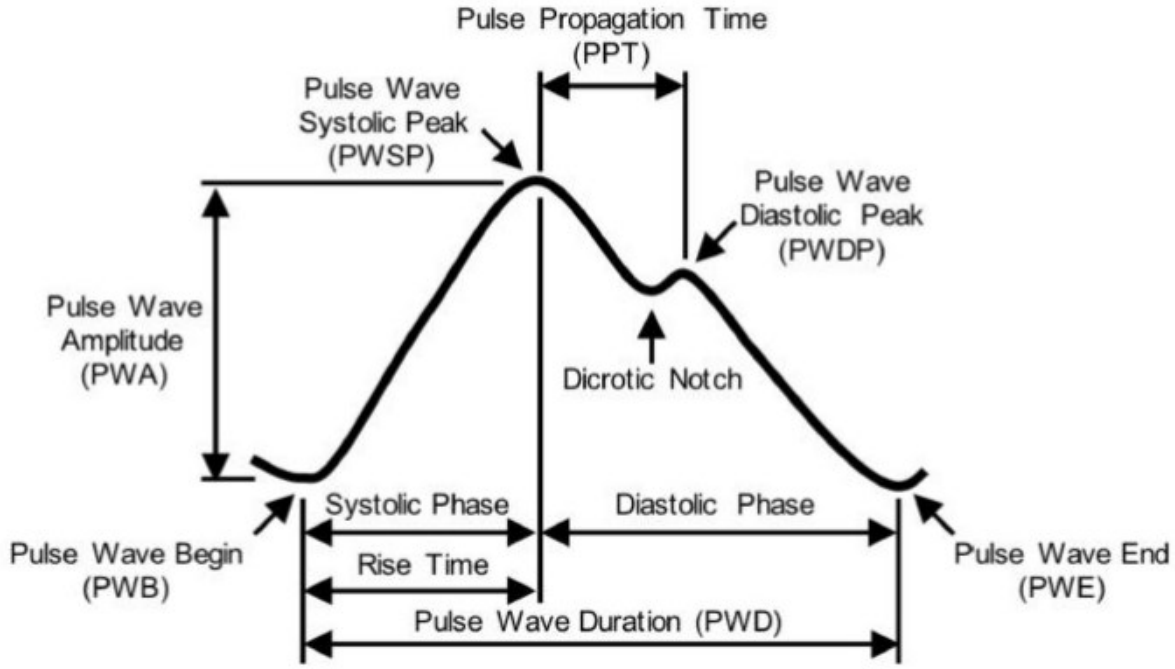


Fig. 2.8 Pulse wave characteristic of the pulse wave AC component [16].

2.3 HEART RATE

HR is an important physiological parameter that indicates the rhythm at which the heart pumps venous blood into the lungs and oxygenated blood into the systemic circulation, and as such reflects the body's metabolic demand [18].

HR is the number of heartbeats per unit of time, expressed typically as beats per minute, bpm. Is generated by the spontaneous activity of the sinoatrial pacemaker cells and constantly varies under the influence of certain nonmodifiable(age, sex and race) and modifiable factors(such as, lifestyle factors, physical activity, mental stress and so on) [19].

A normal resting HR for adults' ranges between 60 and 100 bpm.

For many years, ECG has been used as a dominant cardiac monitoring technique to identify cardiovascular abnormalities and to detect irregularities in heart rhythms [11]. In recent years, PPG based device is becoming a popular technology for continuous HR monitoring.

HR can be derived from the time intervals among consecutive heartbeats in the ECG or among pulsations in the photopletysmogram [19].

In detail HR can be easily estimated from ECG signal through the following three methods [20]:

1- A quick method that is quite popular. Measure the number of large squares that form the R-R interval and remember the following series:
   - 1 square →HR: 300bpm
   - 2 squares →HR: 150 bpm
   - 3 squares →HR: 100 bpm
   - 4 squares →HR: 75 bpm
   - 5 squares →HR: 60 bpm
   - 6 squares →HR: 50 bpm

2- Counting the number of large squares between two consecutive R waves and then dividing 300 by the number of squares found:

$$HR = \frac{300}{number\ of\ large\ squares\ between\ consecutive\ R\ waves} \quad (4)$$

3- Counting the number of small squares between two consecutive R waves and then dividing 1500 by the number of small squares found:

$$HR = \frac{1500}{number\ of\ large\ squares\ between\ consecutive\ R\ waves} \quad (5)$$

As mentioned above it is possible to estimate HR also from PPG signal. The AC component of the PPG signal is synchronous with the beating heart and thus can provide a HR estimation. One of the main problems of HR estimation is the motion artifacts that can compromise the reliability of the assessment.

Several computer algorithms have been designed to reduce artifacts. Once the optical signals have been improved different HR estimation approaches can be applied. These approaches include frequency- and time-domain methods. The former estimates the spectral density of the signal with either a non-parametric (fast Fourier, discrete cosine, or wavelet transforms) or parametric method (autoregressive model). The latter operating in the time-domain can be based on the detection of the temporal interval between two events related to the heartbeat such as maxima, minima or zero-crossing or on the tracking of the instantaneous dominant frequency [9].

2.4 CARDIOVASCULAR SIGNALS IN THE SPORT FIELD

HR is one of the most important indices to evaluate the cardiovascular function in athlete. While an adult's resting HR ranges between 60 and 100 bpm, an athlete's resting HR can be between 40 and 60 bpm.

HR recording through wearable devices is a non-invasive and time-efficient tool for cardiac monitoring in the sport field. These devices are equipped with miniaturized sensors and powerful

signal processing applications [21]. Two typologies of sensor can be found within the devices: movement sensors and physiological sensors. Movement sensors comprise pedometers, accelerometers/gyroscope and GPS, instead physiological sensors comprise HR monitor, temperature monitor and integrated sensors [21].

The real-time monitoring of HR allows the athlete to precisely control his training intensity to optimize training and prevent training loads that are too low or high [9].

Advances in technology have enables individual athletes, sport teams and physicians to monitor movements, workloads, and biometric markers of players in an effort to maximize performance and minimize injuries. Monitoring these variables may allow the identification of biomechanical fatigue and early intervention to prevent injuries during training and competition. Monitoring may also facilitate the development of improved training regimens to optimize athlete performance [22].

3 SYSTEMATIC LITERATURE SEARCH AND REVIEW ON WEARABLE SENSORS FOR RECORDING OF CARDIAC SIGNALS WHILE PRACTING SPORT

3.1 MATERIALS AND METHODS

The systematic review was conducted according to the Preferred Reporting Item for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [23].

3.1.1 Literature Search Strategy

The systematic literature search was carried out on three electronic databases: PubMed (provided by the National Institutes of Health and the U.S. National Library of Medicine), Scopus (provided by Elsevier) and Web of Science (provided by Thomson Reuters). Search strategies were developed to retrieve content on wearable device and on their applicability during sport practice. The searches in the electronic databases were performed on 3 November 2022 without any publication data restrictions. The search strategies included a combination of the following keywords combined in 3 concepts:

- sport*, athlete*;
- wearable, portable, sensor*, electronic*, device*;
- heart rate, *cardio*.

The search strings were constructed combining the keywords in a concept with the Boolean operator OR and combining the concepts with the Boolean operator AND as reported in detailed in Table 1. Title and abstract were the searching fields considered in the search strings.

Table 1. Search strings for the selected databases.

DATABASE	SEARCH STRING
PubMed	((sport*[Title/Abstract]) OR (athlet*[Title/Abstract])) AND (((wearable[Title/Abstract]) OR (portable[Title/Abstract])) AND ((sensor*[Title/Abstract]) OR (electronic*[Title/Abstract]) OR (device*[Title/Abstract]))) AND ((heart rate[Title/Abstract]) OR (*cardio*[Title/Abstract]))
SCOPUS	TITLE-ABS ((sport* OR athlet*) AND ((wearable OR portable) AND (sensor* OR electronic* OR device*)) AND (heart AND rate OR *cardio*))
WEB OF SCIENCE	TI= ((sport* OR athlet*) AND ((wearable OR portable) AND (sensor* OR electronic* OR device*)) AND (heart AND rate OR *cardio*)) OR AB= ((sport* OR athlet*) AND ((wearable OR portable) AND (sensor* OR electronic* OR device*)) AND (heart AND rate OR (electrocardio* OR cardio*)))

3.1.2 Selection of Studies

Documents obtained were imported into Mendeley reference management system for duplicate removal. All titles and abstracts of each document were screened and the articles that did not meet the inclusion criteria were excluded.

Eligibility criteria:

1. Papers focusing on commercially available wearable or portable devices.
2. Papers proposing wearables used during sport practice and not general physical activity.
3. Papers proposing wearable devices able to acquire cardiac signals.

Studies that used wearable devices during everyday life setting, for motor activity or in medical practice were excluded. Furthermore, books and reviews were also excluded. Finally, of the remaining publications a full text review was performed based on the same eligibility criteria.

3.1.3 Data Analysis

Studies were categorized based on the application of the wearable or portable devices in validation studies, clinical studies and development of algorithms and databases. Validation studies include those studies where a device was validated or used as reference for validation of other sensors. They were described in terms of used device, measured parameters and sport activities. Clinical studies include those studies where cardiovascular parameters acquired through wearable or portable devices in athletic population are analyzed. They were described in terms of used device, measured parameters, sport activities and population. Studies on development of algorithms and databases include all those studies in which an algorithm was tested for processing of cardiac signals acquired through wearable or portable devices during sport or a database including this type of signals is constructed. They were described in terms of used device, measured parameters and sport activities. Further, each device was described in terms of acquired cardiovascular signals, wear location, target user, output, other acquisition, feedback, associated app, certification and cost.

3.2 RESULTS

The database searches yielded 623 studies: 145 on PubMed, 253 on Scopus and 225 on Web of Science. After removing duplicates, 344 articles remained. Title and abstract review narrowed the results to 151 and 128 papers, respectively. Of the 128 that remained for full-text screening, 91 were

further excluded: 5 publications were not available, 2 because were books, 3 non-English studies, 5 review, and 76 were deemed irrelevant because they focused on the electronic components of the devices or aimed at the development of new devices for research. As a result, a total of 37 studies were included in this systematic review. The entire processes of literature search and study selection are summarised in Figure 4.1.

In Table 2 are reported criterion, measured parameter, sport/activity, aim and summary of results of the 11 papers categorised as validation studies.

In Table 3 are reported device, measured parameter, sport/activity, population, aim and summary of results of the 15 papers categorised as clinical studies.

In Table 4 are reported device, measured parameter, sport/activity, aim and summary of results of the 11 papers categorised as algorithm and database studies. Finally, in table 5 are summarized all the devices that emerged from the various papers with their specs.

To conclude, two pie charts shown in figure 3.1 and in figure 3.2 were created to highlight the analysed sport and the device brands used in the articles examined, respectively.

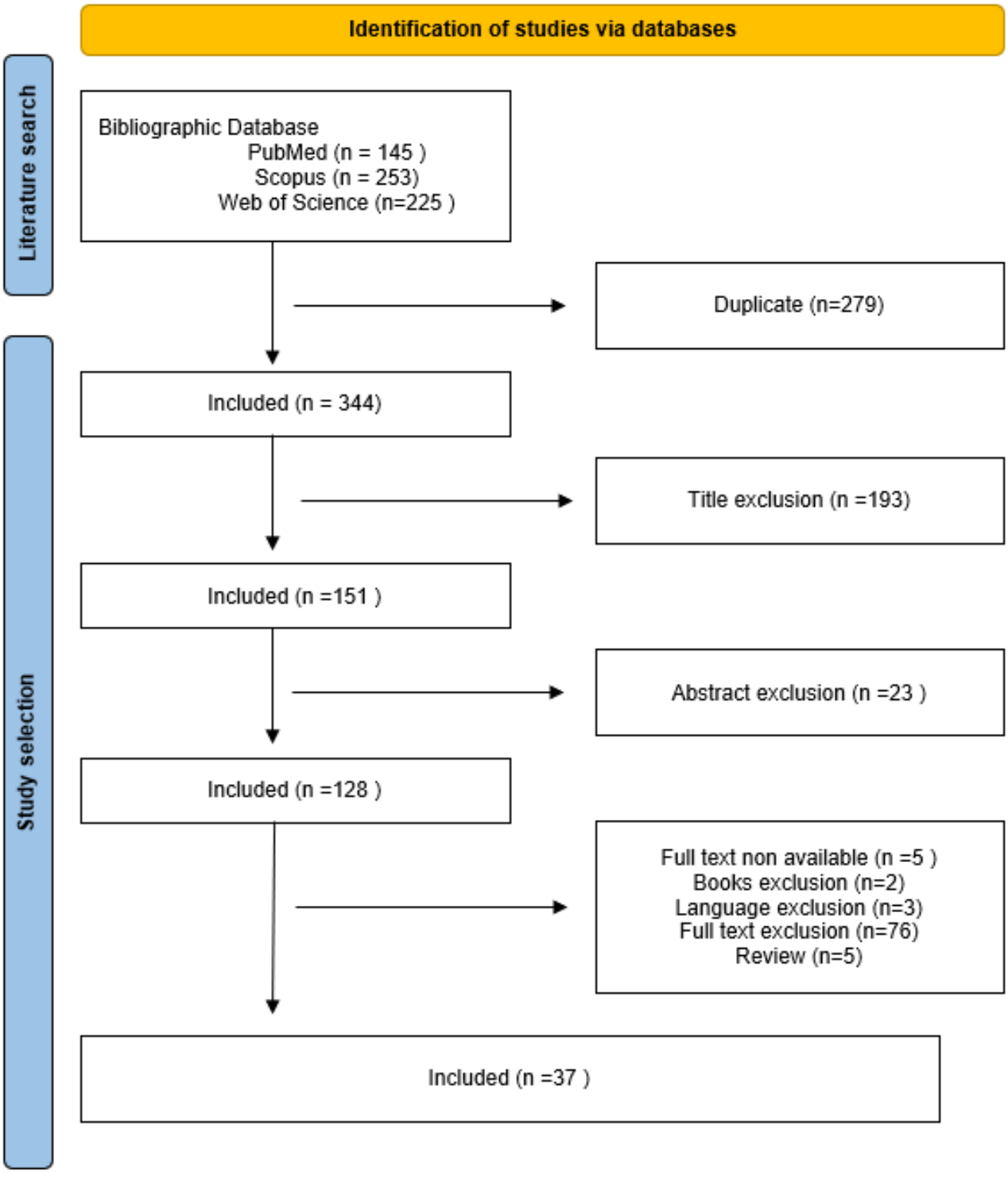


Figure 4.1 Summary literature search and study selection.

Table 2. Devices used, measured parameter and sport activity of the validation studies.

Reference	Device	Criterion	Measured parameter	Sport/activity	Aim	Results summary
[24]	Polar Vantage V2 Garmin Venu Sq	Polar H10 chest strap	HR	Swimming	To evaluate the performances in HR assessment, in terms of accuracy and precision of 2 smartwatches, during swimming activity; compared to Polar H10 chest strap.	For the Polar Vantage V2 -Accuracy of -5 bpm at rest in dry conditions with a precision of ± 19 bpm. -Accuracy of -18 bpm with a precision of ± 68 bpm for in-water tests during activity. For the Garmin Venu Sq -Accuracy and precision are equal to -1 bpm and ± 16 bpm at rest in dry conditions - Accuracy of -57 bpm with a precision of ± 68 bpm for activity in water.
[25]	Apple Watch III Fitbit Iconic Garmin Vivosmart HR TomTom Spark 3	Polar H7 chest-strap A 3 lead ECG	HR	Running	To measure the accuracy of the HR monitor feature in 4 watches at 6 different treadmill speeds; compared to Polar H7 chest strap and a 3 lead ECG	The Polar H7 chest strap had the greatest agreement with the ECG (r_c=98). Apple watch III (r_c=96); The Fitbit Iconic, Garmin Vivosmart HR, and TomTom Spark 3 all had the same level of agreement (r_c=89).
[26]	Kardia 6-lead device	12-lead ECG	ECG	Cricket	To examine and compare the level of similarity between resting 6L and 12L readings in athletes.	Relatively high levels of agreement for QTc and PR interval and QRS duration, with the 6L readings slightly but significantly shorter on average. The largest difference was seen in the QTc intervals (391 ms vs 401 ms, p = 0.003). QRS duration were shorter on average by 3 ms (89 ms vs 92 ms, p = 0.025) and PR intervals were shorter on average by 6 ms (163 ms vs 169 ms, p < 0.001). The QRS axis was normal in 26/30 (87%) of athletes in both 6L and 12L, while the remaining 4/30 (13%) showed evidence of right axis deviation.
[27]	Garmin Fenix 5 Jabra Elite Sport earbuds Motiv Ring Scosche Rhythm+ Suunto Spartan Sport watch	Polar H7 chest-strap	HR	Trail running	To determine HR validity of 5 wearable devices during a trail run; compared to Polar H7 chest strap.	Garmin Fenix 5 (MAPE = 13%, LOA = -32 to 162, rC = 0.32), Jabra Elite Sport (MAPE = 23%, LOA = -464 to 503, rC = 0.38), Motiv ring (MAPE = 16%, LOA = -52 to 96, rC = 0.29), Scosche Rhythm+ (MAPE = 6%, LOA = -114 to 120, rC = 0.79), Suunto Spartan Sport (MAPE = 2%, LOA = -62 to 61, rC = 0.96).

Continue Table 2. Devices used, measured parameter and sport activity of the validation studies.

Reference	Device	Criterion	Measured parameter	Sport/activity	Aim	Results summary
[28]	PulseOn: Optical wrist worn heart rate monitor	Polar V800 HR monitor	HR	Running	To estimate HR, EE, and VO_{2max} during running and to evaluate the accuracy of the estimated parameters compared to Polar V800.	PulseOn was able to measure HR during running with a 1.9%MAPE. VO_{2max} estimated during the submaximal outdoor running test was closely similar to the sports laboratory estimate (MAPE 5.2%). EE was quite accurate when HR was above the aerobic threshold (MAPE 6.7%), but MAPE increased to 16.5% during a lighter intensity of exercise.
[29]	Polar sport watch	Polar H10 chest strap	HRV	Specific training program (3 sessions of 60–90 min per week with all-out sprint intervals and squats and bench press strength exercises)	To determine the level of agreement between different methods of HRV monitoring (Polar Nightly Recharge™ and Kubios app) in 2 different system.	Very large correlation (r = 0.714) and good reliability (ICC = 0.817) were obtained between devices through the entire training program. But there was a 60.6% of discordance in the likelihood interpretation of the change for the 66 weeks evaluated
[30]	Polar OH1 Fitbit Charge 3	Polar H10 chest strap	HR	Light, moderate, vigorous, and sprint-based exercise	To assess the validity of the 2 devices for measuring HR against Polar H10 chest strap.	Very good correlation between the Polar OH1 and Polar H10 devices (r=0.95), with a mean bias of −1 beats·min^{-1} and limits of agreement of −20 to 19 beats·min^{-1}. The Fitbit Charge 3 device underestimated HR by 7 beats·min^{-1} compared with Polar H10, with a limit of agree ment of −46 to 33 beats·min^{-1} and poor correlation (r=0.8). The MAPE for both devices was deemed acceptable (<5%). Polar OH1 performed well across each phase of trial 1; however, validity was worse for trial 2 activities. Fitbit Charge 3 performed well only during rest and non-sprint-based treadmill activities
[31]	Polar Vantage M watch	3 leads plus V5 ECG	HR	Treadmill exercise intensities	To assess the test-retest reliability of the watch to measure HR during various treadmill intensities.	ICC values for PVM during stages 1, 2 and 5 demonstrated good to excellent test–retest reliability (0.78, 0.78 and 0.92; 95% CI (0.54–0.90, 0.54–0.9, 0.79–0.97)). For PVM during stages 0 (rest), 3 and 4, the ICC values indicated poor to good reliability (0.42, 0.68 and 0.58; 95% CI (−0.27–0.73, 0.32–0.85, 0.14–0.80)).

Continue Table 2. Devices used, measured parameter and sport activity of the validation studies.

Reference	Device	Criterion	Measured parameter	Sport/activity	Aim	Results summary
[32]	Adidas Smart sports bra Sensoria fitness sports bra Berlei sports bra	Polar H7 chest strap	HR	Walking and running	To determine the validity of HR measures in 3 commercially available sports bras.	The Adidas Smart sports bra was valid only during rest ([ICC]=0.79, [MAPE]=4.5%, [LoA]=−8 to 8). The Berlei sports bra was valid across all conditions (ICC =0.99, MAPE=0.66%, LoA=−19 to 19), and the Sensoria biometric bra was valid during rest and walking (ICC =0.96, MAPE=1.9%, LoA=−15 to 12).
[33]	Polar H10 chest strap	12-lead ECG	HRV	Resting state and incremental exercise	To compare the HRV data obtained by the chest strap using the Elite application against a 12-channel ECG and analyzed by Kubios HRV software.	High correlations were found for the resting conditions (PRE: r = 0.95, r_c = 0.95, $ICC_{3,1}$ = 0.95, POST: r = 0.86, r_c = 0.84, $ICC_{3,1}$ = 0.85) and for the incremental exercise (r > 0.93, r_c > 0.93, $ICC_{3,1}$ > 0.93). While PRE and POST comparisons revealed no differences, significant bias could be found during the exercise test for all variables (p < 0.001). For RR and HR, bias and limits of agreement (LoA) in the Bland–Altman analysis were minimal (RR: bias of 0.7 to 0.4 ms with LoA of 4.3 to -2.8 ms during low intensity and 1.3 to -0.5 ms during high intensity, HR: bias of -0.1 to -0.2 ms with LoA of 0.3 to -0.5 ms during low intensity and 0.4 to -0.7 ms during high intensity). DFA a1 showed wider bias and LoAs (bias of 0.9 to 8.6% with LoA of 11.6 to -9.9% during low intensity and 58.1 to -40.9% during high intensity)
[34]	Scosche Rhythm+ Apple Watch Fitbit Blaze Garmin Forerunner 235 TomTom Spark Cardio	Polar H7 chest strap 12-lead ECG	HR	Aerobic exercise	To assess the accuracy of five 5 optically based HR monitors.	Polar H7 (rc = 0.996) > Apple Watch (rc = 0.92) > TomTom Spark (rc = 0.83)> Garmin Forerunner (rc = 0.81) > Scosche Rhythm+ (rc = 0.75) > Fitbit Blaze (rc = 0.67)

Table 3. Devices used, measured parameter, sport activity and population of the clinical case studies.

Reference	Device	Measured parameter	Sport/activity	Population characteristics	Aim	Results summary
[35]	Huawei sport watch	HR	Table tennis	High level table tennis (Demographic and anthropometric data not reported)	The real-time monitoring of athletes' HR using intelligent wearable devices	The real-time HR monitoring of intelligent wearable devices for athletes training is beneficial to the formulation of scientific training plans, the recovery of sports injuries, the improvement of sports training effect, and the prevention of overtraining.
[36]	Polar S810i	HR	Speed skating marathon	Highly trained male athlete (20y, 73,4 kg, 178 cm, VO_2 peak: 60.8 mL·kg^{-1}·min^{-1})	To quantify and describe the exercise intensity by monitoring the oxygen uptake, HR and speed	The average HR was 171 ± 6 bpm corresponding to the 95% of the maximum.
[37]	Polar Team Pro sensor	HR	Basketball	10 athletes (Age: 19.8 ± 1.3; body mass 78.1 ± 5.8 kg; height 179.1 ± 6.0 cm; $V\dot{O}_2$ 47.2 ± 4.7 mL·kg^{-1}·min^{-1}; HRpeak 196.0 ± 8.9 b·min^{-1})	To monitor NCAA division, I women's basketball athletes throughout each 4- quarter game with wearable microsensor technology and assess HR responses and time spent in 5 different HR zones	Athlete's averaged 34.5 minutes per game and peaked at 69.2 minutes in HRZone5, which was $85% of their HRmax. There were no differences in average and maximal heart rates across quarters
[38]	Polar Team Pro sensor	HR	Basketball	13 female basketball athletes (ages 19.6 ± 1.3; 18–22 years old)	To assess factors that contribute to countermovement jump performance	Fixed-effects models revealed a main effect of group ($p \leq 0.05$) for CMJ_{avg}, CMJ_{max}, VO_{2max}, weekly percent changes in body weight and for 3-day training load, HRavg, and playing time at >85% HR_{max}. When athletes experienced minimal changes in CMJ performance, relative to large changes, they produced greater power, jumped higher, avoided negative changes in weekly body weight.

Continue Table 3. Devices used, measured parameter, sport activity and population of the clinical case studies.

Reference	Device	Measured parameter	Sport/activity	Population characteristics	Aim	Results summary
[39]	BioHarness 3.0 By Zephyr	HR, ECG	Running, soccer, cycling.	10 sedentary subjects (Age [25-31] year; weight [70-78] kg; height [167-183] cm; HR upper limit [189-195] bpm) and 10 amateur athletes (Age [24-36] year; weight [57-75] kg; height [165-185] cm; HR upper limit [184-196] bpm).	To develop and test a low-cost, large-scale procedure for HR and HRV monitoring from signals obtained using comfortable wearable sensors, finalized to evaluate the health status of an athlete besides his/her performance level.	Compared to SS, AA showed a better health-status, quantified in a lower resting HR (63 bpm vs. 73 bpm; $P < 0.005$) and a higher resting HRV (29 ms vs. 23 ms; $P < 0.05$), and a better performance level, quantifies in a lower recovery time (130 ms vs. 174 ms; $P < 0.05$).
[40]	Polar S810	HR	Badminton	7 professional badminton players (age 16.9 ± 2.1 years; body mass 62.8 ± 9.2 kg; stature 1.71 ± 0.09 m)	To assess cardiorespiratory and metabolic responses during on-court badminton rally simulations at different intensities. To compare HR vs $\dot{V}O_2$ relationships obtained from laboratory and on-court measurements.	Cardiorespiratory parameters measured during the rallies reached 95% of maximal IIAT values. The HR vs $\dot{V}O_2$ slope and intercept differed in the on-court and the IIAT conditions ($P = 0.012$ and $P = 0.008$, respectively).
[41]	Polar H10 chest strap	HR	Running, basketball, and badminton	14 recreationally active male participants (age: 24.9 ± 2.4 years, height: 1.77 ± 0.04 m, mass: 74.6 ± 6.9 kg, resting HR: 72.1 ± 11.1 bpm)	To quantify the strength of the relationship between the percentage of HR reserve (%HRR) and two acceleration-based intensity metrics (AIMs) under three intensity conditions (locomotion speeds).	During running, both AIMs at the shank and PL at the wrist had strong correlations (r = 0.777–0.778) with %HRR; while other combinations were negligible to moderate (r = 0.065–0.451). For basketball, both AIMs at the shank had stronger correlations (r = 0.604–0.628) with %HRR than at wrist (r = 0.536–0.603) and trunk (r = 0.403–0.463) with %HRR. During badminton exercise, both AIMs at shank had stronger correlations (r = 0.782–0.793) with %HRR than those at wrist (r = 0.587–0.621) and MAD at trunk (r = 0.608) and trunk (r = 0.314).
[42]	BioHarness 3.0 By Zephyr	ECG	Basket, cycling, fitness, jogging, middle-distance running, tennis, and CrossFit.	51 athletes (38 males and 13 females) 29±11 years old	To support large-scale prevention programs fighting sport-related sudden cardiac death by providing a set of electrocardiographic features representing a starting point in the development of normal reference values for the pre-exercise phase.	For athletes 35 years old or younger, preliminary values were [72;91]bpm, [26;47]ms, [85;104]ms, [-0.08;0.08]mm, [326;364]ms and [378;422]ms, respectively. For athletes older than 35 years old, preliminary values were [71;94]bpm, [16;65]ms, [85;100]ms, [-0.11;0.07]mm, [330;368]ms and [394;414]ms, respectively.

Continue Table 3. Devices used, measured parameter, sport activity and population of the clinical case studies.

Reference	Device	Measured parameter	Sport/activity	Population characteristics	Aim	Results summary
[43]	Polar chest belt	HR	Running in Hilly Terrain	17 competitive runners (female: n=4, V'O2max: 55±6 mL·kg^{-1}·min^{-1}; male: n=13, V'O2max: 68±6 mL·kg^{-1}·min^{-1})	To investigate the cardiorespiratory and metabolic response. To evaluate whether HR adequately reflects the exercise intensity or whether the tissue saturation index could provide a more accurate measure.	The exercise intensity within the uphill and downhill sections was 94±2% and 91±3% of HRmax, 84±8% and 68±7% of V'O2max, respectively. The oxygen uptake (V'O2) increased within the uphill and decreased within the downhill sections (P< .01). While HR was unaffected by the altering slope conditions, the TSI was inversely correlated to the changes in V'O2 (r = - .70, P< .05).
[44]	Polar Team Pro sensor	HR	Football	20 players U19	To provide an understanding of how Polar Team Pro is being implemented in competitive football training process, in terms of evaluation and monitoring the official games' parameters.	Managing this physiologic parameter combined with distances covered, speed zones, number of sprints, leads to certain measure taken by the coach such as squad rotation in order to manage fatigue and injury risks.
[45]	Hexoskin wearable body metrics	HR	Badminton	A right-handed elite badminton player	To investigate of the relationship between movement accuracy and HR.	There is a significant negative relationship between the movement similarity index and the HR, r(28) = .78, p < 0.001
[46]	Polar H10 chest strap	HR	Walking and running	120 athletes+non athletes Sedentary group, male: 40.0%, female: 60.0% exercise-habit group, male: 46.7%, female: 53.3% non-endurance group, male: 56.7%, female: 43.3% endurance group, male: 63.3%, female: 36.7%	To include the HR reserve as a compensatory parameter for physical intensity and derived new equations customized for sedentary, regularly exercising, non-endurance athlete, and endurance athlete adults.	EE predictive equations were revised using linear regression with cross-validation on VM, HRR, and body mass (BM). The modified model demonstrates valid and reliable predictions across four populations (Pearson correlation coefficient, r: 0.922 to 0.932; intraclass correlation coefficient, ICC: 0.919 to 0.930).
[47]	Kardia device	ECG	Cricket and Running	1 (26-year-old) male elite non-endurance athlete 2(16- and 28-year-old) male elite cricketers 1 (48-year-old) amateur middle-distance 2 of which one male and one female (38- and 28-year-old) semi-elite ultra-endurance runners	To highlights the use of the device in aiding the diagnosis of arrhythmias in the setting of exercise-related symptoms in athletes.	An accurate diagnosis of an arrhythmia was obtained in five cases using the smartphone ECG. No arrhythmia was identified in the final case despite using the device during multiple symptomatic events

Continue Table 3. Devices used, measured parameter, sport activity and population of the clinical case studies.

Reference	Device	Measured parameter	Sport/activity	Population characteristics	Aim	Results summary
[48]	Polar Team Pro sensor	HR	Soccer, basketball and volleyball	64 male collegiate students (20.7±1.9 years, height: 171.3±6.2 cm, weight: 62.6±6.1 kg)	To quantify the physical and physiological response during three widely practiced leisure-time sports using the global positioning system and HR monitors.	(1) Collegiate students covered 2776±184 m, 3408±350 m, and 1103±267 m of TD in soccer, basketball and volleyball games: 98.4±1.2% of the TD in volleyball games was covered at the speed of <6km/h, which was the highest among the three games; 7.8±1.9%, 12.0±2.3%, 4.3±1.4%, 1.52±0.69% and 0.90±0.51% of the TD in basketball games was covered at the speed zones of 6-7.9 km/h, 8-11.9 km/h, 12-14.9 km/h, 15-18 km/h, and >18 km/h which was the highest among the three games, while collegiate students achieve 12.7±5.3 efforts of medium intensity (a=1.5-3.5m/s2) deceleration in soccer games which was the most among the three games; (2) the mean HR of collegiate students in soccer, basketball and volleyball games were 172±11 beats/min, 162±16 beats/min, and 136±16 beats/min, respectively. The mean HR and % of game duration in HIHR and VHIHR in volleyball were significantly lower (p<0.001) than in soccer and basketball.
[49]	Polar Team Pro sensor	HR	Basketball	11 female basketball athletes (age: 19.6 ± 1.4 years, body mass: 78.5 ± 5.7 kg, height: 179.7 ± 6.0 cm, $V\dot{O}_2$peak: 47.3 ± 5.1 mL·kg^{-1}·min^{-1}, HRpeak: 195 ± 8.6 b·min^{-1})	To assess caloric expenditure throughout 31 games.	There were significant main effects of 10-minute quarters on calories (p , 0.001) and % HRavg (p 5 0.015) but not playing intensity ≥85% HRpeak (p 5 0.125) and % HRpeak (p 5 0.629). Caloric expenditure the only variable to increase from the first to the fourth quarter. There were main effects of individual athletes on calories, % HRavg, % HRpeak, live time, and playing intensity ≥ 85% HRpeak (p , 0.001 for all).

Table 4. Device used, measured parameters and sport activities of the algorithm and database studies.

Reference	Device	Measured parameter	Sport/activity	Aim	Summary description of database and algorithm
[50]	Hexoskin biometric compression shirt	HR	Climbing	To develop a novel method to examine time-resolved sensor-based measurements of multiple biometrics at different micro locations (finely spaced positions; MLs) along a climbing route, which is called the ML-specific biometric system (MLBS).	The study demonstrates the ability of MLBS to determine multiple time-resolved biometrics at different ML_s
[51]	Garmin watch	HR	Running	To monitor the running situation of sportsman, an automatic feature selection has been proposed for running sprint reorganization.	The automatic feature selection mode can automatically screen useful features to achieve better classification accuracy, effectively identify the sprint period in the running segment, and the recognition accuracy rate reaches 83.7%.
[52]	BioHarness 3.0 by Zephyr	ECG, HR	Aerobic exercise	To propose CaRiSMA 1.0 as a tool with the dual scope of helping contrasting Sport-related sudden cardiac death (SRSCD) and educating a current training.	CaRiSMA 1.0 analyzes the electrocardiographic and HR signals acquired during a training session and provides intuitive graphical outputs consisting of two traffic lights, one related to cardiac health, based on resting QTc and one related to training, based on exercise HR.
[53]	BioHarness 3.0 by Zephyr	ECG and automatically computes HR series	Aerial silks, basketball, CrossFit, fitness, jogging, middle-distance running, running, soccer, tennis, and Zumba	To provide a database of cardiorespiratory data.	The database is a collection of 126 cardiorespiratory data (demographic info-cardiorespiratory signals and training notes) acquired from 81 subjects while practicing 10 different sports.
[54]	Polar T31™ Coded band	HR	Swimming	To propose an intelligent data analytics system for swimmer performance.	The intelligent data analytics system includes pre-processing of raw signals, feature representation of wearable sensors and biosensors, online recognition of the swimming style and turns, and post-analysis of the performance for coaching decision support, including stroke counting and average speed.

Continue Table 4. Device used, measured parameters and sport activities of the algorithm and database studies.

Reference	Device	Measured parameter	Sport/activity	Aim	Summary description of database and algorithm
[55]	Polar H10 chest strap	ECG, HR	Running	To explore the performance of the promising BR estimation methods during physical effort. So, to compare and validate pre-processing and BR estimation algorithms using HR recorded with a chest belt during physical activities.	The two methods (BPF + STFT and rRR + HFT) were found to provide reasonably accurate BR estimation over a wide range of breathing frequencies measured during a running VO2max test. When an accuracy of more than 5.5% is not required.
[56]	Samsung Galaxy Watch 3	HR	High intensity workout	To develop an ultra-lightweight framework for a precise real-time HR monitoring during the high intensity physical exercises.	The model is a combination of a digital signal processing and deep convolutional and recurrent neural networks approaches. Results obtained exceed the current state of the art solutions both in terms of the achieved accuracy of HR estimation and consumed computational resources
[57]	BioHarness 3.0 by Zephyr	HR	Soccer	To present a predictive analytics framework for analysing and predicting soccer players' performance data.	The method compares the HR with the speed parameters. By inserting the ratio into a neural network, it is possible to obtain information regarding the athlete's conditioning.
[21]	BioHarness 3.0 by Zephyr	HR	Middle-distance running and jogging	To develop an algorithm for automatic detection of training phases in HR series to boost signal processing for athletic cardiovascular monitoring with wearable technologies.	The fully automatic algorithm for detection of training phases can boost HR signal processing for reliable computation and interpretation of HR- derived indices.
[58]	Garmin Forerunner 305 device	HR	Aerobic activity	To present a system able to estimate the intensity of activities and to identify physical activity and posture.	First results shown on both the intensity estimation and activity recognition tasks, with a performance of 87; 54% and 86; 80%, respectively.
[59]	Polar T31™ Coded band	HR	Swimming	To propose a novel system that allows the technical staff to monitor and analyse the swimmer's inertial and bio-signal in real time.	The algorithm integrates inertial data and biosignal for monitoring swimmer's activity. A computational application displays in real time physiological and inertial information such as: swimming style, average speed and stroke counting

Table 5. Summary of the specs of each device (acquired cardiovascular signals- wear location-target user-output-other acquisition- feedback- associated app, certification-cost).

DEVICE	ACQUIRED CARDIAC SIGNALS (HR, ECG)	DERIVED SIGNAL	SENSOR	WEAR LOCATION	TARGET USER	OUTPUT	OTHER ACQUISITIONS	FEEDBACK	ASSOCIATED APP	FDA	Cost
Apple Watch I	HR	-	OPTICAL HEART SENSOR	WRIST-WORN	ATHLETE	YES Numeric HR on the watch face	ACCELEROMETER GYROSCOPE	The Irregular Rhythm Notification Feature analyzes pulse rate data to identify episodes of irregular heart rhythms suggestive of AFib, and it provides a notification to the user when it detects an episode.	Apple watch app Health app	NO	Discontinued
Apple Watch III	HR	-	OPTICAL HEART SENSOR	WRIST-WORN	ATHLETE	YES Numeric HR on the watch face	ALTIMETER GPS/GLONASS/GALILEO GYROSCOPE Estimation of VO2	The Irregular Rhythm Notification Feature analyzes pulse rate data to identify episodes of irregular heart rhythms suggestive of AFib, and it provides a notification to the user when it detects an episode.	Apple watch app Health app	NO	Discontinued
BioHarness 3.0 by Zephyr	ECG	HR	SINGLE LEAD ECG	CHEST STRAP	ATHLETE	NO	BREATHING SENSOR (Respiration rate) 3-AXIS ACCELEROMETER (body orientation and activity)	The BioHarness module outputs a subject status indication which has the values: -Green: subject's physiological parameters are within thresholds as configured -Orange: one or more of the subject's parameters have crossed the configured threshold values. -Red: one or more of the subject's parameters have exceeded threshold values for a sustained period (configurable).	Bluetooth Test Application	NO	Not available

Continue Table 5. Summary of the specs of each device.

DEVICE	ACQUIRED CARDIAC SIGNALS (HR, ECG)	DERIVED SIGNAL	SENSOR	WEAR LOCATION	TARGET USER	OUTPUT	OTHER ACQUISITIONS	FEEDBACK	ASSOCIATED APP	FDA	Cost
Fitbit Blaze	HR	-	OPTICAL HR SENSOR	WRIST-WORN	ATHLETE	YES Numeric HR on the watch face	MEMS 3-AXIS ACCELEROMETER (Steps taken, calories burned, sleep data) ALTIMETER (floors climbed)	In the Fitbit app you can check your current HR zones. The target HR zones are: Out of zone, fat burn, cardio, and peak zone.	Fitbit app	NO	Discontinued
Fitbit Charge 3	HR	-	OPTICAL HR SENSOR	WRIST-WORN	ATHLETE	YES Numeric HR on the watch face	MEMS 3-AXIS ACCELEROMETER (Steps taken, , calories burned, sleep data) ALTIMETER (floors climbed)	In the Fitbit app you can check your current HR zones. The target HR zones are: Below, fat burn, cardio, and peak zone.	Fitbit app	NO	Discontinued
Fitbit Iconic	HR	-	OPTICAL HR SENSOR	WRIST-WORN	ATHLETE	YES Numeric HR on the watch face	MEMS 3-AXIS ACCELEROMETER (Steps taken, calories burned, sleep data) ALTIMETER (floors climbed, GPS/ GLONASS (Distance covered)	In the Fitbit app you can check your current HR zones. The target HR zones are: Below, fat burn, cardio, and peak zone.	Fitbit app	NO	Product recall

Continue Table 5. Summary of the specs of each device.

DEVICE	ACQUIRED CARDIAC SIGNALS (HR, ECG)	DERIVED SIGNAL	SENSOR	WEAR LOCATION	TARGET USER	OUTPUT	OTHER ACQUISITIONS	FEEDBACK	ASSOCIATED APP	FDA	Cost
Garmin Fenix 5	HR	-	OPTICAL HR SENSOR	WRIST-WORN	ATHLETE	YES Numeric HR and graph of HR on the watch face	GPS/GLONASS/GALILEO (Distance travelled) GARMIN ELEVATE WRIST BAROMETRIC ALTIMETER (floors climbed,) COMPASS GYROSCOPE ACCELEROMETER (Step count, calories burned, sleep data) THERMOMETER Estimation of VO2	The device alert you when your HR exceeds a certain number of bpm after a period of inactivity. The device detecting your maximum HR, can set your HR zone.	Garmin Connect Mobile app	NO	499,99-549,99€
Garmin Forerunner 235	HR	-	OPTICAL HR SENSOR	WRIST-WORN	ATHLETE	YES Numeric HR and graph of HR on the watch face	GPS/GLONASS (distance travelled) GARMIN ELEVATE WRIST ACCELEROMETER (Step count, and calories burned) THERMOMETER Estimation of VO2	The device detecting your maximum HR, can set your HR zone.	Garmin connect™ Mobile	NO	239,99 €
Garmin Forerunner 305	HR (With the use of a compatible CHEST STRAP)	-	-	WRIST-WORN+ HR CHEST STRAP	ATHLETE	YES Numeric HR on the watch face	GPS (distance travelled, altitude)	The HR alert notifies you if your HR exceeds or drops below a specific number of bpm and can also notify you if your HR exceeds or drops below a certain HR zone. The device detecting your maximum HR, can set your HR zone.	Garmin Express on computers	NO	Discontinued

Continue Table 5. Summary of the specs of each device.

DEVICE	ACQUIRED CARDIAC SIGNALS (HR, ECG)	DERIVED SIGNAL	SENSOR	WEAR LOCATION	TARGET USER	OUTPUT	OTHER ACQUISITIONS	FEEDBACK	ASSOCIATED APP	FDA	Cost
Garmin Venu Sq	HR	-	OPTICAL HR SENSOR	WRIST-WORN	ATHLETE	YES Numeric HR and graph of HR on the watch face	GPS/GLONASS/GALILEO (distance travelled) GARMIN ELEVATE WRIST COMPASS ACCELEROMETER (Step count, calories burned, sleep data) THERMOMETER PULSE OX BLOOD SATURATION MONITOR Estimation of VO2 Respiration rate	Abnormal HR Alert alerts you when your HR exceeds or drops below a certain number of bpm. The device detecting your maximum HR, can set your HR zone.	Garmin Connect™	NO	199,99- 249,99€
Garmin Vivosmart HR	HR	-	OPTICAL HR SENSOR	WRIST-WORN	ATHLETE	YES Numeric HR on the watch face	GARMIN ELEVATE WRIST BAROMETRIC ALTIMETER (floors climbed ACCELEROMETER (Step count, distance travelled, calories)	The device alert you when your HR is above or below a target zone or a custom range. The device detecting your maximum HR, can set your HR zone.	Garmin Connect™	NO	149,00€
Garmin watch	-	-	-	WRIST-WORN	-	-	-	-	-	-	-
Hexoskin	ECG	HR	Single Lead ECG	Biometric compression shirt	ATHLETE	YES Numeric HR and ECG signal on the app of the smartphone	Dual Channel Respiratory Inductance Plethysmography (RIP) (breathing rate) 3-Axis Accelerometer (cadence, steps) Estimation of VO2	The device detecting your maximum HR, can set your HR zone.	Hexoskin app	NO	$ 199.00-648.00
Huawei sport watch	-	-	-	WRIST-WORN	-	-	-	-	-	-	-
Jabra Elite Sport Earbuds	HR	-	OPTICAL HR SENSOR	Earbuds	ATHLETE	NO	-	-	Jabra Sport Life app	NO	Discontinued
Kardia by AliveCor	ECG	HR	Single Lead ECG	Mobile ECG recorder	DOCTOR	YES Numeric HR and ECG signal on the app of the smartphone	-	Normal sinus rhythm, Atrial Fibrillation, and Unreadable Detectors.	Kardia app	FDA-cleared	155,00 €

Continue Table 5. Summary of the specs of each device.

DEVICE	ACQUIRED CARDIAC SIGNALS (HR, ECG)	DERIVED SIGNAL	SENSOR	WEAR LOCATION	TARGET USER	OUTPUT	OTHER ACQUISITIONS	FEEDBACK	ASSOCIATED APP	FDA	Cost
Kardia 6L by AliveCor	ECG	HR	Single or 6 Lead ECG	Mobile ECG recorder	DOCTOR	YES Numeric HR and ECG signal on the app of the smartphone	-	Normal sinus rhythm, atrial fibrillation, bradycardia, tachycardia, no analysis, unclassified result or unreadable	Kardia app	FDA-cleared	210,00€
Motiv Ring	HR	-	OPTICAL HR SENSOR	RING	ATHLETE	YES Numeric HR on the app of the smartphone	-	-	Motiv 24/7 Smart Ring	NO	$199.99
Polar H10	HR	-	Single Lead ECG	CHEST STRAP	ATHLETE	YES Numeric HR on the receiving device (ex. Smartphone)	-	-	Polar Beat app Polar Flow app	NO	89.90 €
Polar H7	HR	-	Single Lead ECG	CHEST STRAP	ATHLETE	YES Numeric HR on the receiving device (ex. Smartphone)	-	-	Polar Beat app Polar Flow app	NO	Discontinued
Polar OH1	HR	-	OPTICAL HEART SENSOR	FOREARM BAND	ATHLETE	YES Numeric HR on the receiving device (ex. Smartphone)	-	-	Polar Flow app Polar beat app	NO	59.90 €
Polar S810	HR (With the use of a compatible CHEST STRAP)	-	-	WRIST-WORN + HR CHEST STRAP	ATHLETE	YES Numeric HR on the watch face	-	A beeping sound or a flashing activates if your heartbeat is outside the HR limit.	-	NO	Discontinued
Polar S810i	HR (With the use of a compatible CHEST STRAP)	-	-	WRIST-WORN + HR CHEST STRAP	ATHLETE	YES Numeric HR on the watch face	-	A beeping sound or a flashing activates if your HR is outside the set limits	-	NO	Discontinued

Continue Table 5. Summary of the specs of each device.

DEVICE	ACQUIRED CARDIAC SIGNALS (HR, ECG)	DERIVED SIGNAL	SENSOR	WEAR LOCATION	TARGET USER	OUTPUT	OTHER ACQUISITIONS	FEEDBACK	ASSOCIATED APP	FDA	Cost
Polar T31 coded™	HR	-	ECG technology	CHEST STRAP	ATHLETE	YES Numeric HR on the receiving device (ex. Smartphone)	-	-	Polar Flow app Polar beat app	NO	44.90 €
Polar Team Pro sensor	HR	-	ECG technology	CHEST STRAP	COACH	YES Numeric HR on the receiving device	GPS(speed, distance) ACCELEROMETER (running cadence) GYROSCOPE	-	PC software (for planning and recording) PDA software (for online monitoring)	NO	299 €
Polar V800	HR (With the use of a compatible CHEST STRAP)	-	-	WRIST-WORN + HR CHEST STRAP	ATHLETE	YES Numeric HR on the watch face	GPS(speed, distance and altitude) ACCELEROMETER(running cadence, calories burned) Estimation of VO2	-	Polar Flow app	NO	Discontinued
Polar Vantage M	HR	-	OPTICAL HEART SENSOR)	WRIST-WORN	ATHLETE	YES Numeric HR on the watch face a	GPS/GLONASS/GALILEO (speed, distance and altitude) ACCELEROMETER (running cadence, calories burned) Estimation of VO2	The device detecting your maximum HR, can set your HR zone.	Polar Flow app	NO	279.90 €
Polar Vantage V2	HR	-	OPTICAL HEART SENSOR	WRIST-WORN	ATHLETE	YES Numeric HR on the watch face	GPS/GLONASS/GALILEO (Speed, distance and altitude) ALTIMETER (running cadence, calories burned) COMPASS Estimation of VO2	The device detecting your maximum HR, can set your HR zone.	Polar Flow app	NO	499.90 €

Continue Table 5. Summary of the specs of each device.

DEVICE	ACQUIRED CARDIAC SIGNALS (HR, ECG)	DERIVED SIGNAL	SENSOR	WEAR LOCATION	TARGET USER	OUTPUT	OTHER ACQUISITIONS	FEEDBACK	ASSOCIATED APP	FDA	Cost
PulseOn:	HR-ECG		OPTICAL SENSOR and ECG ELECTRODES	WRIST-WORN	DOCTOR	YES Numeric HR on the watch face	-	If an episode of irregular rhythm is detected, the device notifies the patient to take an ECG recording.	PulseOn app	NO	Not available
Samsung Galaxy Watch 3	HR	-	OPTICAL HR SENSOR	WRIST-WORN	ATHLETE	YES Numeric HR and ECG signal on the watch face	GPS/GLONASS/GALILEO (distance, speed) ACCELEROMETER (Step count, calories burned) GYROSCOPE	Sinus Rhythm Atrial Fibrillation Inconclusive Poor recording	Samsung Health Monitor app	NO	[370,00 – 409,00] €
Scosche Rhythm+	HR	-	OPTICAL HR SENSOR	FOREARM BAND	ATHLETE	YES Numeric HR on the app of the receiving device	-	-	Compatible with over 200+ Fitness Apps	NO	Not available
Sensoria fitness sports bra	HR	-	-	BRA	ATHLETE	YES Numeric HR on the app of the smartphone	-	-	Sensoria Fitness mobile app	NO	$69.00
Suunto Spartan Sport	HR	-	OPTICAL HEART SENSOR	WRIST-WORN	ATHLETE	YES Numeric HR on the watch face	GPS/ GLONASS (distance, speed) ACCELEROMETER (Steps count, calories burned, sleep data) ALTIMETER COMPASS	The device detecting your maximum HR, can set your HR zone.	Suunto app	NO	Not available
TomTom Spark 3 Cardio	HR	-	OPTICAL HEART SENSOR	WRIST-WORN	ATHLETE	YES Numeric HR on the watch face	GPS (distance, speed) ACCELEROMETER (Steps count, calories burned) Estimation of VO2	The device detecting your maximum HR, can set your HR zone.	TomTom Sports app	NO	129.00€

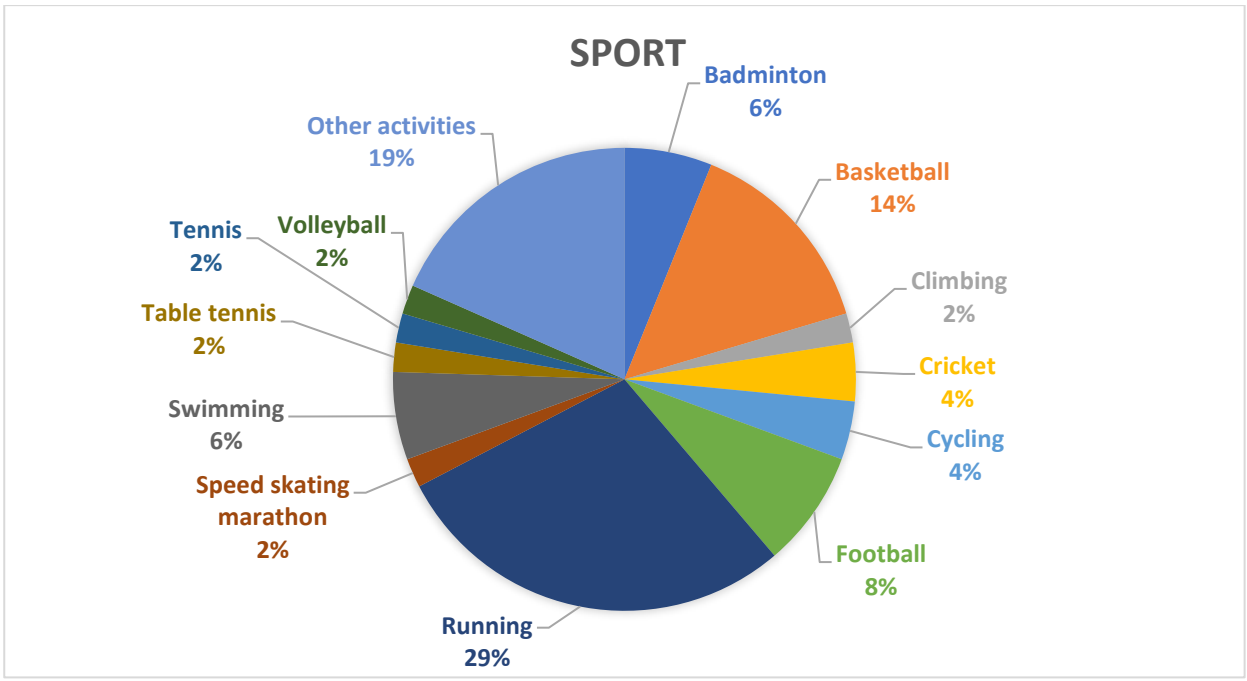


Fig. 3.1 Pie chart related to sport analysed by wearable devices.

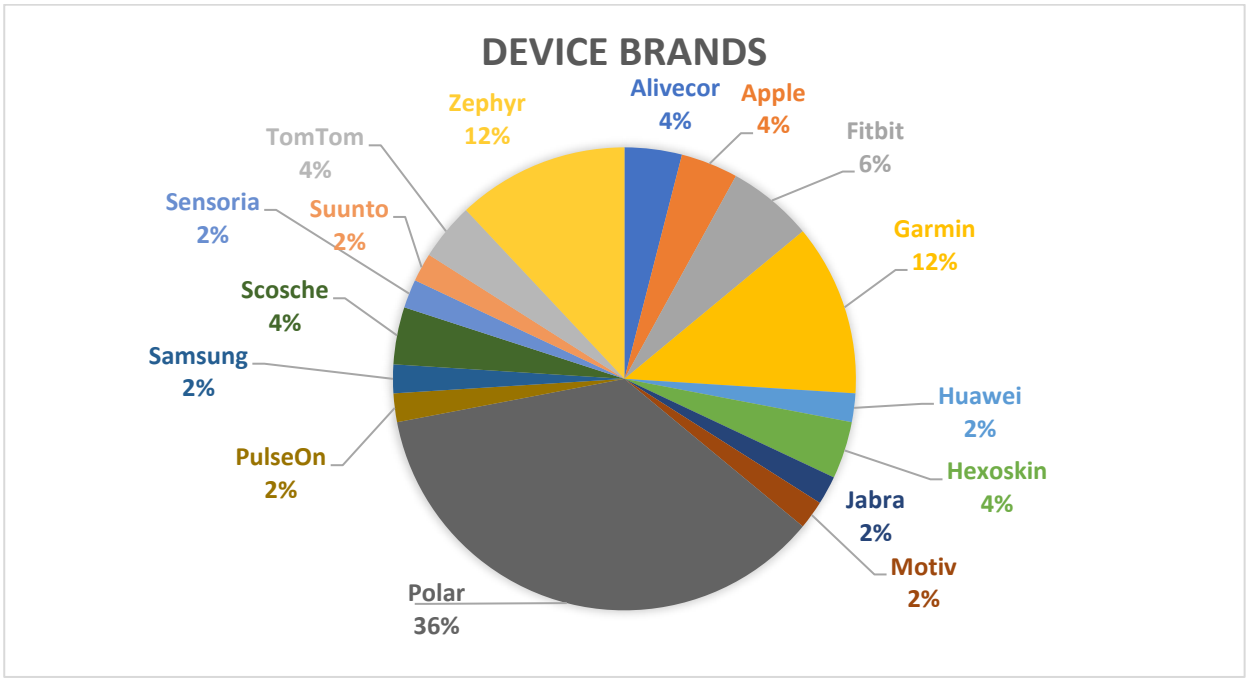


Fig. 3.2 Pie chart related to wearable device brands.

3.3 DISCUSSION

In the last few decades, the use of wearable technology devices that allow real-time acquisition of vital parameters has increased significantly, in particular in medicine and sport field. The purpose of this study was to summarize the commercial wearable devices recording cardiac signals, ECG and HR, used during sport activity. To achieve the aim of this study a systematic literature search and review has been done. Overall, 37 papers were included. The studies were classified into validation studies (n=11), clinical case studies (n=15), and algorithms or database studies (n=11).

3.3.1 VALIDATION STUDIES

A rigorous assessment of validity should be the mutual interest of manufacturers, scientific institutions, and consumers in order to judge whether a wearable device for assessment of HR is useful and performs with satisfactory accuracy.

It is strongly advisable to validate wearable devices against standard apparatus such as ECG through multiple lead channels or simple chest straps consisting of two electrodes. 12 lead ECG is the current gold-standard reference for assessing HR, however for sport activities several studies use as a criterion chest strap HR monitors; as has been demonstrated in [25], [34] the Polar H7 chest strap shows a Lin's concordance correlation coefficient r_c=0,98 and r_c=0,99 respectively compared to 12 lead ECG. In the recent papers, Polar H7 it was superseded by the later model Polar H10 [24] [29] [30] which for incremental exercise shows a Lin's concordance correlation coefficient r_c=0,93 compared to 12 lead ECG [33].

The validation process has been performed on many wearable devices, most of them were wrist-worn devices based on PPG technology. Between them Apple Watch III proved to be the optimal choice for assessing HR during high-speed running (r_c=96) [25].

Accuracy and precision of Polar Vantage V2 and Garmin Venu Sq have been analysed during swimming providing worsen results; water and arms movement act as relevant interference inputs. Therefore, for monitoring swimming athletes HR is recommended to use specific wearable devices [24].

Overall, these finding highlights that the validation process provides heterogeneous results due to the different types of activities and the intensity of these. Also appears the variability in the expression of the metrological characteristics, *e.g.,* referring to accuracy some authors use mean absolute percentage error (MAPE), others Pearson's coefficient (r) or Lin's concordance correlation coefficient (r_c). As the data are quite inhomogeneous, can be scarcely compared. Moreover, the

number of the wearable devices is rapidly growing; companies and consumers would benefit from guiding standards.

Hence the development of a validation protocol for wearables measuring HR is needed. For this aim, six university and one industrial partner join to present a set of guidelines in order to obtain more comparable data. The statement focused on six standardised domains: target population, criterion measure, index measure, testing conditions, data processing and statistical analysis [60].

3.3.2 CLINICAL CASES STUDIES

The papers classified in clinical case studies aim to monitor and improve the athlete's performance using wearable devices. The employ of wearable technology is becoming increasingly integrated into fitness and sports as they can be employed to quantify exercise intensity and analysed physical activity.

Studies were conducted for various sports using different type of wearables; among the various devices it is important to highlight recurrent use of the Polar Pro Sensor [37] [38] [44] [48].

This sensor is included in the Polar Team Pro system that allowed a real time HR monitoring of multiple athletes simultaneously. Therefore, this system is widely used in team sports, such as basketball, football, and volleyball. In this manner the coaches can track athletes' parameters during game and training session.

Two other devices of remarkable interest are BioHarness 3.0 and AliveCore Kardia since they are wearables able to record ECG signal. The former was used during running, soccer, and cycling to evaluate the health status of an athlete and to provide a tool to contrast sudden cardiac death in sport (SCD). [39] BioHarness 3.0 was also used for the investigation of ECG signal during the pre-exercise phase, providing reference values that could help the identification of sport-related cardiac complications. [42]

ECG recording has also been acquired using a portable device called AliveCore Kardia, that help the diagnosis of arrhythmias during exercise in athlete [47].

In conclusion, through the use of these technologies, it is possible to plan training programs, reduce the risk of injury, and in some cases predict the risk of SCD.

3.3.3 ALGORITHMS AND DATABASE STUDIES

Algorithm and database studies are the third category of the research. Among them only one study focused on proposing an open-source database that can be useful for new studies. Data reported

were acquired through the chest strap BioHarness 3.0 that directly records the ECG and automatically computes HR and breathing rate (BR). The ECG signals have been recorded from athletes practicing 10 different sports [53].

As for regard the algorithms, each study was conducted with a different aim and different devices were used.

Hexoskin biometric compression shirt was used in [50] to demonstrate the capability of the ML-specific biometric system.

BioHarness 3.0 was used in [52] for the proposal of a tool called CaRiSMA 1.0, in [57] for the presentation of a predictive analytics framework for predicting soccer players' performance data, and in [21] for the development of an algorithm for automatic detection of training phases.

Polar H10 was used in [55] for and indirect estimation of BR from HR acquired by the chest belt during running. Instead, for an automatic monitoring of running situation a Garmin watch has been used [51].

Polar T31^{TM} Coded band was used in [54] for the proposal of an intelligent data analytics system for swimmer performance and in [59] for the proposal of a novel system that allows the technical staff to monitor and analyse the swimmer's inertial and bio-signal in real time.

Instead, Samsung Galaxy Watch 3 in [56], for a precise real-time HR monitoring during the high intensity physical exercises and Garmin Forerunner 305 [58] device to estimate the intensity of activities were used.

The lack of databases suggests that future authors should develop open-source databases with the goal of making more information regarding sports activity available. Such data could be useful for further studies, such as the development of new automatic algorithms.

3.3.4 LIMITATION

One limitation of the study is that some articles may have been excluded from the search because the title or abstract stated the specific name of the device and sport, while the search strings were created with generic terms, refer to section 3.1.1.

3.4 CONCLUSION

To conclude, in these years, from 2011 to 2022 at the research level, 34 different commercial devices have been employed. In particular, 21 wrist-worn, 5 chest-straps, 2 forearm bands, 2 mobile

ECG recorders, 1 biometric shirt, 1 bra, 1 earbuds and 1 ring. As a first, it is important to note the number of wristbands investigated and utilized, which suggests that they are becoming increasingly popular. The user's choice of which device to pick also depends on the type of activity. If a precise monitoring is needed, a chest strap like Polar H10 is recommended, which provides better accuracy even in high intensity training.

Although chest-bands offer greater accuracy in HR monitoring and cost less, wristbands, because of their multifunctionality and comfort, prove more desirable.

Of all the devices, ten are found to be discontinued and one recalled, namely Fitbit Ionic, whose battery could overheat, posing a burn hazard to consumers. The devices still in production can be connected to another system via a specific application to display the data obtained during acquisition. In some wrist device it is also possible to check data directly on the own monitor.

Among all the devices, the Kardia by AliveCor stood out for its target user and FDA cleared. This portable technology is able to detect atrial fibrillation, bradycardia, tachycardia and normal heart rhythm. Most others, on the other hand, estimating user’s maximum HR report your actual HR zone, that is a set range of heart beats per minute. Many runners and other athletes are using HR zones to measure and increase their cardiovascular strength and improve their level of fitness.

REFERENCES

[1] Ambrosi G, Cantino D, Castano P, Correr S, D'Este L, Donato R. F, Familiari G, Fornai F, Gulisano M, Iannello A, Magaudda L, Marcello M. F., Martelli A. M, Pacini P, Rende M, Rossi P, Sforza C, Tacchetti C, Toni R. e Zummo G. (2006). Anatomia dell'uomo. Seconda edizione. Edi-Ermes.

[2] Barni T, Billi A. M, Castellucci M, Cocco L, Dolci S, Fumagalli L, Manzoli L, Palumbo C, Papa M, Nori S. L, Rezzani R, Rossi P, Sbarbati A, Zancanaro C. e Zummo G. (2009). Anatomia del Gray- Le basi anatomiche per la pratica clinica. Quarantesima edizione. Elsevier.

[3] J. Gordon Betts, Kelly A. Young, James A. Wise, Eddie Johnson, Brandon Poe, Dean H. Kruse, Oksana Korol, Jody E. Johnson, Mark Womble, Peter DeSaix. (2013). *Anatomy & Physiology.* OpenStax.

[4] Aicardi G, Danieli D, Ferraina S, Gastaldi G, Laforenza U, Marini H. R, Marini R, Pagliaro P, Pessia M, Pettorossi V. E, Ruggeri P. e Zocchi L. (2012). Fisiologia medica. Dodicesima edizione. Elsevier.

[5] Battaglini P. P, Belluardo N, Benedetti F, Benfenati F, Bottinelli R, Caminiti R, Capelli C, Cecchi G, Cherubini E, Colantuoni A, Conti F, Corbellini G, d'Ascanio P, Eusebi F, Fanò G, Federici A, Ferretti G, Fesce R, Franzini C, Gallese V, Giuffrida R, Grassi C, Lacquaniti F, Luppino G, Maioli C, Malgaroli A, Manzoni D, Menini A, Montarolo P. G, Pettorossi V. E, Ricci V, Rossi F, Scarnati E, Sternini C, Tassinari G, Tempia F, Tononi G, Vacca G, Veicsteinas A, Vitiello F e Zoccoli G. (2005). Fisiologia Medica. Edi-Ermes.

[6] Branca F. P, Cannella M, Galo J, Marinozzi F, Rubegni S e Silvestri S. (2000). Fondamenti di ingegneria clinica. Springer Verlag.

[7] Aicardi G, Danieli D, Ferraina S, Gastaldi G, Laforenza U, Marini H. R, Marini R, Pagliaro P, Pessia M, Pettorossi V. E, Ruggeri P. e Zocchi L. (2012). Fisiologia medica. Dodicesima edizione. Elsevier.

[8] Dale Dubin, M.D. (2018). Interpretazione dell'ECG. Sesta edizione. Monduzzi.

[9] Lemay, M., Bertschi, M., Sola, J., Renevey, P., Parak, J., & Korhonen, I. (2014). Chapter 2.3 - Application of Optical Heart Rate Monitoring. In E. Sazonov & M. R. Neuman (Eds.), Wearable Sensors (pp. 105–129).

[10]Allen, J. (2007). Photoplethysmography and its application in clinical physiological measurement. Physiological Measurement, 28, R1-39.

[11]Castaneda D, Esparza A, Ghamari M, Soltanpur C, Nazeran H. A review on wearable photoplethysmography sensors and their potential future applications in health care. Int J Biosens Bioelectron. 2018;4(4):195-202. doi: 10.15406/ijbsbe.2018.04.00125. Epub 2018 Aug 6. PMID: 30906922; PMCID: PMC6426305.

[12] N. Saquib, M. T. I. Papon, I. Ahmad and A. Rahman, "Measurement of heart rate using photoplethysmography," *2015 International Conference on Networking Systems and Security (NSysS)*, Dhaka, Bangladesh, 2015, pp. 1-6, doi: 10.1109/NSysS.2015.7043525.

[13] Park J, Seok HS, Kim SS, Shin H. Photoplethysmogram Analysis and Applications: An Integrative Review. Front Physiol. 2022 Mar 1;12:808451. doi: 10.3389/fphys.2021.808451. PMID: 35300400; PMCID: PMC8920970.

[14] Donida Labati, R., Piuri, V., Rundo, F., & Scotti, F. (2022). Photoplethysmographic Biometrics: A comprehensive survey. Pattern Recognition Letters, 156, 119–125.

[15] Spigulis J. Optical non-invasive monitoring of skin blood pulsations. Appl Opt. 2005 Apr 1;44(10):1850-7.

[16] Fischer C, Domer B, Wibmer T, Penzel T. An Algorithm for Real-Time Pulse Waveform Segmentation and Artifact Detection in Photoplethysmograms. IEEE J Biomed Health Inform. 2017 Mar;21(2):372-381.

[17] Fischer, C., Glos, M., Penzel, T., & Fietze, I. (2017). Extended algorithm for real-time pulse waveform segmentation and artifact detection in photoplethysmograms. Somnologie, 21, 1–11.

[18] Sartor, F., Gelissen, J., van Dinther, R. et al. Wrist-worn optical and chest strap heart rate comparison in a heterogeneous sample of healthy individuals and in coronary artery disease patients. BMC Sports Sci Med Rehabil **10**, 10 (2018).

[19] Valentini M, Parati G. Variables influencing heart rate. Prog Cardiovasc Dis. 2009 Jul-Aug;52(1):11-9.

[20] Boron, W.F. and Boupaep, E.L. (2016) Medical Physiology. 3rd Edition, Elsevier Publisher, Philadelphia.

[21] Romagnoli, S., Sbrollini, A., Scalese, A., Marcantoni, I., Morettini, M., & Burattini, L. (2021). Signal Processing for Athletic Cardiovascular Monitoring with Wearable Sensors: Fully Automatic Detection of Training Phases from Heart Rate Data. Proceedings - 2021 IEEE International Conference on Bioinformatics and Biomedicine, BIBM 2021, 1491–1494.

[22] Li RT, Kling SR, Salata MJ, Cupp SA, Sheehan J, Voos JE. Wearable Performance Devices in Sports Medicine. Sports Health. 2016 Jan-Feb;8(1):74-8.

[23] Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ 2021, 372, 71.

[24] Cosoli, G., Antognoli, L., Veroli, V., & Scalise, L. (2022). Accuracy and Precision ofWearable Devices for Real-Time Monitoring of Swimming Athletes. Sensors, 22(13).

[25] Pasadyn, S. R., Soudan, M., Gillinov, M., Houghtaling, P., Phelan, D., Gillinov, N., Bittel, B., & Desai, M. Y. (2019). Accuracy of commercially available heart rate monitors in athletes: a prospective study. Cardiovascular Diagnosis and Therapy, 9(4), 379–385.

[26] Orchard, J. J., Orchard, J. W., Raju, H., la Gerche, A., Puranik, R., & Semsarian, C. (2021). Comparison between a 6-lead smartphone ECG and 12-lead ECG in athletes. JOURNAL OF ELECTROCARDIOLOGY, 66, 95–97.

[27] Navalta, J. W., Montes, J., Bodell, N. G., Salatto, R. W., Manning, J. W., & DeBeliso, M. (2020). Concurrent heart rate validity of wearable technology devices during trail running. PloS One, 15(8), e0238569.

[28] Parak, J., Uuskoski, M., Machek, J., & Korhonen, I. (2017). Estimating Heart Rate, Energy Expenditure, and Physical Performance With a Wrist Photoplethysmographic Device During Running. JMIR MHealth and UHealth, 5(7), e97.

[29] Ruiz-Alias, S. A., Marcos-Blanco, A., Clavero-Jimeno, A., & García-Pinillos, F. (2022). Examining weekly heart rate variability changes: a comparison between wearable devices running head: weekly heart rate variability changes. Sports Engineering, 25(1).

[30] Muggeridge, D. J., Hickson, K., Davies, A. V., Giggins, O. M., Megson, I. L., Gorely, T., & Crabtree, D. R. (2021). Measurement of Heart Rate Using the Polar OH1 and Fitbit Charge 3 Wearable Devices in Healthy Adults During Light, Moderate, Vigorous, and Sprint-Based Exercise: Validation Study. JMIR MHealth and UHealth, 9(3), e25313.

[31] Climstein, M., Alder, J. L., Brooker, A. M., Cartwright, E. J., Kemp-Smith, K., Simas, V., & Furness, J. (2020). Reliability of the Polar Vantage M Sports Watch when Measuring Heart Rate at Different Treadmill Exercise Intensities. Sports (Basel, Switzerland), 8(9).

[32] Navalta, J. W., Ramirez, G. G., Maxwell, C., Radzak, K. N., & McGinnis, G. R. (2020). Validity and Reliability of Three Commercially Available Smart Sports Bras during Treadmill Walking and Running. Scientific Reports, 10(1), 7397.

[33] Schaffarczyk, M., Rogers, B., Reer, R., & Gronwald, T. (2022). Validity of the Polar H10 Sensor for Heart Rate Variability Analysis during Resting State and Incremental Exercise in Recreational Men and Women. Sensors (Basel, Switzerland), 22(17).

[34] Gillinov, S., Etiwy, M., Wang, R., Blackburn, G., Phelan, D., Gillinov, A. M., Houghtaling, P., Javadikasgari, H., & Desai, M. Y. (2017). Variable Accuracy of Wearable Heart Rate Monitors during Aerobic Exercise. Medicine and Science in Sports and Exercise, 49(8), 1697–1703.

[35] Zhang, B. (2021). Application of Smart Wearing Real-time Heart Rate Monitoring in Sports Training. Proceedings - 2021 International Conference on Health Big Data and Smart Sports, HBDSS 2021, 177–180.

[36] Stangier, C., Abel, T., Mierau, J., Hollmann, W., & Strüder, H. K. (2016). Cardiorespiratory demands during an inline speed skating marathon race: a case report. The Journal of Sports Medicine and Physical Fitness, 56(9), 1007–1012.

[37] Sanders, G. J., Boos, B., Rhodes, J., Kollock, R. O., & Peacock, C. A. (2021). Competition-Based Heart Rate, Training Load, and Time Played Above 85% Peak Heart Rate in NCAA Division I Women's Basketball. Journal of Strength and Conditioning Research, 35(4), 1095–1102.

[38] Sanders, G. J., Boos, B., Rhodes, J., Kollock, R. O., Peacock, C. A., & Scheadler, C. M. (2019). Factors associated with minimal changes in countermovement jump performance throughout a competitive division I collegiate basketball season. Journal of Sports Sciences, 37(19), 2236–2242.

[39] Maranesi, E., Morettini, M., Agostinelli, A., Giuliani, C., di Nardo, F., & Burattini, L. (2016). Health Monitoring in Sport Through Wearable Sensors: A Novel Approach Based on Heart-Rate Variability. In M. Conti, N. M. Madrid, R. Seepold, & S. Orcioni (Eds.), MOBILE NETWORKS FOR BIOMETRIC DATA ANALYSIS (Vol. 392, pp. 235–246).

[40] Rampichini, S., Limonta, E., Pugliese, L., Cè, E., Bisconti, A. v, Gianfelici, A., la Torre, A., & Esposito, F. (2018). Heart rate and pulmonary oxygen uptake response in professional badminton players: comparison between on-court game simulation and laboratory exercise testing. European Journal of Applied Physiology, 118(11), 2339–2347. https://doi.org/10.1007/s00421-018-3960-6

[41] Chen, W.-H., Chiang, C.-W., Fiolo, N. J., Fuchs, P. X., & Shiang, T.-Y. (2022). Ideal Combinations of Acceleration-Based Intensity Metrics and Sensor Positions to Monitor Exercise Intensity under Different Types of Sports. Sensors (Basel, Switzerland), 22(7).

[42] Romagnoli, S., Sbrollini, A., Colaneri, M., Marcantoni, I., Morettini, M., Zitti, G., Brocchini, M., Pozzi, M., & Burattini, L. (2021). Initial investigation of athletes' electrocardiograms acquired by wearable sensors during the pre-exercise phase. Open Biomedical Engineering Journal, 15, 37–44.

[43] Born, D.-P., Stöggl, T., Swarén, M., & Björklund, G. (2017). Near-Infrared Spectroscopy: More Accurate Than Heart Rate for Monitoring Intensity in Running in Hilly Terrain. International Journal of Sports Physiology and Performance, 12(4), 440–447.

[44] Bota, A., Teodorescu, S., Mezei, M., & Alexe, I. (2019). Polar team pro - the ultimate diagnosis tool in competitive football. ELearning and Software for Education Conference, 456–462.

[45] Yong, T. H., & Tan, D. Y. W. (2018). Preliminary investigation of movement-heart rate relationship using kinect-based badminton performance analysis. Proceeding of 2017 International Conference on Robotics, Automation and Sciences, ICORAS 2017, 2018-March, 1–5.

[46] Chang, C.-H., Hsu, Y.-J., Li, F., Tu, Y.-T., Jhang, W.-L., Hsu, C.-W., Huang, C.-C., & Ho, C.-S. (2020). Reliability and validity of the physical activity monitor for assessing energy expenditures in sedentary, regularly exercising, non-endurance athlete, and endurance athlete adults. PeerJ, 8, e9717.

[47] Jewson, J. L., Orchard, J. W., Semsarian, C., Fitzpatrick, J., la Gerche, A., & Orchard, J. J. (2022). Use of a smartphone electrocardiogram to diagnose arrhythmias during exercise in athletes: a case series. In European heart journal. Case reports (Vol. 6, Issue 4, p. ytac126).

[48] Li, P., Zhang, H., Zhang, D., Jiang, G., He, J., & Liu, H. (2021). Using Wearable Electronic Devices to Quantify the Physical and Physiological Response of Collegiate Students Participating in Leisure-Time Team Sports. Proceedings - 2021 International Conference on Information Technology and Contemporary Sports, TCS 2021, 628–631.

[49] Sanders, G. J., Boos, B., Rhodes, J., Peacock, C. A., Kollock, R. O., & Scheadler, C. M. (2022). Variability of Competition-Based Caloric Expenditure and Relative Heart Rates in National Collegiate Athletic Association Division I Women's Basketball. Journal of Strength and Conditioning Research, 36(1), 162–166.

[50] Breen, M., Reed, T., Breen, H. M., Osborne, C. T., & Breen, M. S. (2022). Integrating Wearable Sensors and Video to Determine Microlocation-Specific Physiologic and Motion Biometrics-Method Development for Competitive Climbing. Sensors (Basel, Switzerland), 22(16).

[51] Yang, Y., & Huang, W. (2022). An Automatic Feature Selection Model for Running Sprint Reorganization Using Wrist Accelerometers. 2022 4th International Conference on Communications, Information System and Computer Engineering, CISCE 2022, 418–426.

[52] Agostinelli, A., Morettini, M., Sbrollini, A., Maranesi, E., Migliorelli, L., Nardo, F. di, Fioretti, S., & Burattini, L. (2017). CaRiSMA 1 . 0 : Cardiac Risk Self-Monitoring Assessment. The Open Sports Sciences Journal, 10, 179–190.

[53] Sbrollini, A., Morettini, M., Maranesi, E., Marcantoni, I., Nasim, A., Bevilacqua, R., Riccardi, G. R., & Burattini, L. (2019). Data in brief Sport Database : Cardiorespiratory data acquired through wearable sensors while practicing sports. Data in Brief, 27, 104793.

[54] Costa, J., Silva, C., Santos, M., Fernandes, T., & Faria, S. (2021). Framework for Intelligent Swimming Analytics with Wearable Sensors for Stroke Classification. Sensors (Basel, Switzerland), 21(15).

[55] Prigent, G., Aminian, K., Rodrigues, T., Vesin, J.-M., Millet, G. P., Falbriard, M., Meyer, F., & Paraschiv-Ionescu, A. (2021). Indirect Estimation of Breathing Rate from Heart Rate Monitoring System during Running. Sensors (Basel, Switzerland), 21(16).

[56] Fedorin, I., Pohribnyi, V., Sverdlov, D., & Krasnoshchok, I. (2022). Lightweight neural network based model for real-time precise HR monitoring during high intensity workout using consumer smartwatches. Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS, 2022-July, 1310–1313.

[57] Ravindranathan, S., Ardakani, H. D., Pimental, A., Lee, J., Mangine, R., & Clark, J. F. (2017). Performance monitoring of soccer players using physiological signals and predictive analytics. MFPT 2017 Annual Conference: 50 Years of Failure Prevention Technology Innovation.

[58] Reiss, A., & Stricker, D. (2011). Towards global aerobic activity monitoring. ACM International Conference Proceeding Series.

[59] Santos, M. O., Costa, J., Fernandes, T. R., Silva, C., & Faria, S. M. M. (2021). Wearable inertial and bio-signal device for real-time swimmer's monitoring. 2021 Telecoms Conference, ConfTELE 2021.

[60] Mühlen JM, Stang J, Lykke Skovgaard E, et al Recommendations for determining the validity of consumer wearable heart rate devices: expert statement and checklist of the INTERLIVE Network British Journal of Sports Medicine 2021;55:767-779.

RINGRAZIAMENTI