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Accuracy of Wrist-Worn Heart Rate Monitors: A Comprehensive Review of Smartwatches in Exercise Monitoring

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ABSTRACT

Wrist-worn heart rate monitors have become integral in personal health monitoring, particularly during exercise and daily activities. This review evaluates the precision of various commercially available smartwatches in assessing heart rate, focusing on their accuracy across different physical activities, such as walking, running, cycling, and elliptical training. A systematic analysis of 29 peer-reviewed studies, encompassing over 900 participants, was conducted to compare devices like the Apple Watch, Fitbit, Garmin, and others. The results demonstrate significant variation in accuracy depending on the device, type of activity, and individual factors such as body mass index and skin tone. The Apple Watch consistently outperformed other devices, showing the lowest mean absolute percentage error (MAPE), particularly during moderate-intensity activities. In contrast, devices such as the Fitbit Blaze exhibited greater error rates, especially during high-intensity exercises or activities involving significant arm movement. Although wrist-worn heart rate monitors provide users with convenient real-time data, limitations such as motion artifacts, device placement, and external factors may affect their reliability.

Keywords: wrist-worn heart rate monitors, exercise, monitoring, heart rate, photoplethysmography, validation

INTRODUCTION

Digitalization and technological progress are extending to more and more areas of life, including personal health and well-being. The number of digital apps for smartphones, fitness trackers, or smartwatches that allow users to assess and evaluate individualized fitness, health, and lifestyle data is constantly increasing [1]. The advent of wearable technology, particularly wrist-worn devices, has revolutionized health monitoring by providing users with the capability to continuously track vital signs. This innovation represents a significant shift towards personalized healthcare, enabling individuals to monitor their health metrics in real-time. In Poland, wearable wrist-worn fitness trackers and smartwatches have become quite popular, with more than a quarter of working-age internet users owning such a device as of 2023 [2]. This trend is driven by the desire for accessible health data and the convenience of having such capabilities integrated into everyday devices. Smartwatches have evolved from simple fitness trackers to sophisticated health monitoring tools that can provide insights into various physiological parameters such as heart rate, electrocardiogram, blood oxygen saturation, respiratory rate, blood pressure, skin temperature, sleep patterns or even the amount of sweat secreted [3]. With continual improvements, wearable technology devices offer a wide array of functions, including the ability to track steps, calories consumed and burned, floors climbed, sleep, and heart rate, as well as providing silent alarms. By using wearable devices, individuals are becoming more health conscious, thus, enabling them to take control of their own health [4]. The ability of smartwatches to collect and transmit health data remotely has opened new avenues for telemedicine, allowing healthcare providers to monitor patients' conditions without the need for physical consultations. It is also a great advantage of wearable technologies that they allow for continuous data collecting which can help tracking the daily physical activity, searching for patterns or detecting a disease [5].

Heart rate (HR) is a critical vital sign that serves as an essential indicator of an individual's physiological state and overall health. It reflects the number of times the heart beats per minute and is crucial for assessing cardiovascular health. HR is a vital sign of paramount importance in sports medicine, serving as a key indicator of an athlete's physiological status and overall performance. Monitoring heart rate provides insights into an athlete's cardiovascular fitness, recovery status, and response to training loads. Elevated heart rates during exercise can indicate increased cardiovascular demand, while abnormal resting heart rates may signal overtraining or potential health issues [6]. For instance, studies have shown that heart rate can reflect the energy expenditure of athletes during various activities, allowing coaches and trainers to tailor training regimens effectively [6]. Furthermore, heart rate variability (HRV), which measures the variation in time between heartbeats, is increasingly recognized as a critical marker of autonomic nervous system function and stress levels, providing valuable information about an athlete's recovery and readiness to perform [7]. In the context of injury prevention and management, heart rate monitoring can also play a crucial role. For example, athletes experiencing exercise-associated hypotension may exhibit significant changes in heart rate, which can be used to guide hydration and recovery strategies [8]. The integration of wearable technology for continuous heart rate monitoring allows for real-time data collection, enabling athletes and coaches to make informed decisions regarding training intensity and recovery protocols [9]. Recent advances in mobile health technology and wearable electronic devices allow heart rhythm monitoring to be undertaken in real time with greater comfort, ease, and engagement [10]. The importance of heart rate as a vital sign in sports medicine cannot be overstated, as it provides essential data for optimizing performance, preventing injuries, and ensuring the health and well-being of athletes.

Advances in technology have enabled non-invasive methods for heart rate measurement, such as photoplethysmography (PPG) and remote monitoring systems, which enhance the feasibility of regular assessments outside traditional clinical environments [11]. Heart rate measurements from wearables are derived from photoplethysmography (PPG), an optical method for measuring changes in blood volume under the skin. PPG technology recognizes the cardiac cycle by the pulsatile pattern of the change in light absorption, which reflects the volumetric alteration in the microvascular beds underneath the skin. With an accurate estimation, each episode of maximum reflected light absorption translates into an R wave [12]. This method is particularly advantageous due to its portability, ease of use, and ability to provide continuous monitoring without the discomfort associated with traditional methods such as electrocardiography [13]. However, PPG is not without its limitations. One significant challenge is the susceptibility of PPG signals to motion artifacts, which can occur during physical activity or even minor movements [14]. A number of studies have shown that PPG sensors are less reliable at higher heart rates and during exercise [15,16]. The accuracy of PPG can be influenced by factors such as skin tone, ambient light conditions, and the placement of the sensor, which may limit its effectiveness in certain populations or settings [14].

A wide variety of smartwatches are commercially available. These devices range from fitness trackers to more medically oriented watches. Although all devices use PPG sensors, there is diversity in functionality beyond this point [17]. Heart rate measurements using smartwatches are influenced by a variety of factors that can impact the accuracy and reliability of the data collected.

Understanding these factors is crucial for both users and developers of wearable technology, as they can significantly affect the interpretation of heart rate data in various contexts. Among these factors we can distinguish skin tone, ambient light conditions, sensor placement and type of physical activity. Throughout the years numerous studies have been conducted, assessing the accuracy of heart rate measurements of wrist-wearables and factors influencing sensitivity and sensibility of wearable smartwatches. In 2021 The Recommendations for determining the validity of consumer wearable heart rate devices was published to ensure that manufacturers, consumers, healthcare providers and researchers use wearables safely and to its full potential [18]. Given the rapid advancement of technology and the vast array of smartwatches currently available, there is a pressing need for studies that evaluate the accuracy of wearable devices on the market today.

OBJECTIVE

The objective of this review is to evaluate the precision of wrist-worn devices in monitoring heart rate during both physical exertion and everyday activities.

METHODS

A systematic literature search of the PubMed, MEDLINE, and Google Scholar databases was performed in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to identify studies reporting the precision of a wrist-worn devices for the assessment of the heart rate. The following terms were used: wrist-worn devices or smartwatches or wearable devices or heart rate monitors or heart rate watches or wrist-worn activity trackers and accuracy or heart rate monitoring or validation. Out of 49 studies, 29 who satisfied the inclusion criteria were selected. Each of the studies reviewed included an analysis of error (either mean percent error, absolute percent error, root mean squared error or relative error rates) or a correlation assessment with the criterion (either Lin's concordance, intraclass correlations, or Pearson Product Moment), or the Bland-Altman method for evaluating agreement and error. Criterion assessment in the studies evaluated included an electrocardiogram (ECG) or Polar chest strap.

CRITERIA FOR STUDY INCLUSION

Studies included in the analysis had to meet the following inclusion criteria: (1) original peer-reviewed articles of prospective or retrospective studies, (2) patients ≥ 18 years of age, (3) reporting results of wrist-worn wearable devices to measure heart rate during both exercise and daily activities, (4) patients described as healthy with no reported physical conditions. Studies were excluded if they were (1) conference abstracts, case reports, editorials, systematic reviews and meta-analyses, (2) non-English language studies, or (3) duplicates of studies already included. (4) participants performed exercise as part of or for rehabilitation.

RESULTS

Out of 49 studies a total of 29 studies were included in this review. A total number of participants enrolled in these studies was 943. All the papers included in this review were published between 2014 and 2023.

The following wearable devices were compared: Mio Alpha, Fitbit Charge HR, Basis Peak, Microsoft Band, TomTom Runner Cardio, Apple Watch, Garmin Forerunner 225, Fitbit Blaze, TomTom Spark Cardio, Fitbit Iconic, Garmin Vivosmart HR, TomTom Spark 3, Fitbit Surge, Samsung Gear, Philips Health Watch, Polar A370, Tempo HR, PulseOn, Garmin Forerunner 235, Polar A360, TomTom Touch, Mio Fuse, Xiaomi Mi Band 2, Polar Vantage V, Garmin Fenix 5, Fitbit Versa, Garmin Forerunner 610, Polar M600 Sport Watch. Wrist activity monitors had a wide range of accuracy, with the Apple Watch having the lowest mean absolute percent error (MAPE) and the Fitbit devices having the highest MAPE. The accuracy of devices dependent on the heart rate values, type of the exercise performed and the age of participants. All wrist and forearm devices had a tendency to estimate heart rate with a greater error at exercise that included greater arm movement. The details of the study are shown in Table 1.

Table 1. Outcomes of the systematic review.

Author	Title	Type of Device	Number of participants	Type of exercise	Results
Stahl et al [19]	How accurate are the wrist-based heart rate monitors during walking and running activities? Are they accurate enough?	Mio Alpha, Fitbit Charge HR, Basis Peak, Microsoft Band, TomTom Runner Cardio	50	Treadmill at 3.2, 4.8, 6.4, 8.0, and 9.6 km/h each for 5 min	TomTom Runner Cardio MAPE of 3.28%; Basis Peak MAPE of 3.61%; Mio Alpha MAPE of 4.6%; Microsoft Band MAPE of 4.8%; Fitbit Charge HR MAPE of 6.2% TomTom Runner Cardio and Microsoft Band had the strongest correlation with the criterion measure (r=0.959 and r=0.956, respectively). During the 3.2 km/h walking phase, the MAPE rose for all activity monitors, most notably for the Mio Alpha (15.97%). The highest percentage of error occurred in the Fitbit Charge HR in the 3 (9.99%) and 6.4 km/h (10.06%) walking phase, respectively.

Dooley et al [20]	Estimating Accuracy at Exercise Intensities: A Comparative Study of Self-Monitoring Heart Rate and Physical Activity Wearable Devices	Apple Watch, Fitbit Charge HR, Garmin Forerunner 225	62	Treadmill at 2.5 mph, 3.5 mph, 5.5 mph, each stage for 4 min	Apple Watch, MAPE between 1.14% and 6.70%. Fitbit Charge HR MAPE between 2.38% and 16.99%. Garmin Forerunner 225 MAPE between 7.87% and 24.38%.
Gillinov et al [21]	Variable Accuracy of Wearable Heart Rate Monitors during Aerobic Exercise	Apple Watch, Fitbit Blaze, Garmin Forerunner 235, TomTom Spark Cardio	50	Treadmill, stationary bicycle and elliptical trainer	Agreement with ECG for Apple Watch (rc = 0.92), the TomTom Spark (rc = 0.83), the Garmin Forerunner (rc = 0.81), Fitbit Blaze (rc = 0.67). On treadmill, all devices performed well (rc = 0.88-0.93) except the Fitbit Blaze (rc = 0.76). While bicycling, only the Garmin, Apple Watch, and had acceptable agreement (rc > 0.80). On the elliptical trainer without arm levers, only the Apple Watch was accurate (rc = 0.94). None of the devices was accurate during elliptical trainer use with arm levers (all rc < 0.80).
Pasadyn et al [22]	Accuracy of commercially available heart rate monitors in athletes: a	Apple Watch, Fitbit Iconic, Garmin Vivosmart HR,	50	Treadmill at 4, 5, 6, 7, 8, and 9 mph, each for 2 min	Apple Watch demonstrated the highest degree of agreement with the ECG (rc = 96). Fitbit Iconic, Garmin Vivosmart HR and Tom

	prospective study	TomTom Spark 3			Tom Spark 3 all had the same level of agreement (rc=89).
Shcherbina et al [23]	Accuracy in Wrist-Worn, Sensor-Based Measurements of Heart Rate and Energy Expenditure in a Diverse Cohort	Apple Watch, Basis Peak, Fitbit Surge, Microsoft Band, Mio Alpha 2, PulseOn, Samsung Gear S2	60	Treadmill at 3.0 mph for 10 min, 4.0 mph, 5.7 mph, 6.9 mph for 5 min and cycle ergometer workload88 W and 160 W for 5 min	Six of the devices achieved a median error below 5% for HR on the cycle ergometer task; the Samsung Gear S2 achieved a median error rate of 5.1%. For the walking task, three of the devices achieved a median error rate below 5%: Apple Watch, 2.5%; PulseOn, 4.9%; and Microsoft Band, 5.6%. The remaining four devices had median error between 6.5% and 8.8%. Across devices and modes of activities, the Apple Watch achieved the lowest error in HR, 2.0%, while the Samsung Gear S2 had the highest HR error, 6.8%. The lowest error in measuring HR was observed for the cycle ergometer task, 1.8%, while the highest error was observed for the walking task, 5.5%.
Wallen et al [24]	Accuracy of Heart Rate Watches: Implications for Weight Management	Apple Watch, Fitbit Charge HR, Samsung Gear S, Mio Alpha	22	Treadmill and cycle ergometer	The percentage error for HR was small across the devices (range: 1–9%)

Claes et al [25]	Validity of heart rate measurements by the Garmin Forerunner 225 at different walking intensities	Garmin Forerunner 225	12	Treadmill at 4 km/h, at a gradient of 5% and intensity of 4–6 METs, at a gradient of 8% and intensity of seven METs or more, each for 10 min	The mean values per three minutes of every condition did not differ significantly between Garmin Forerunner 225 and the ECG RMSE was 3.01 bpm The Bland-Altman bias was 1.57 bpm LoA raging from 32.53 to 29.40 compared with the ECG.
Hendrixk et al [26]	Clinical Evaluation of the Measurement Performance of the Philips Health Watch: A Within-Person Comparative Study	Philips Health Watch	29	Treadmill at 4.5 km/h, at 3 km/h with uphill 5%, Ergometer bike at 60 rpm, Cross trainer at 60 W, Household activities (mixture), for 3 minutes each Outdoor activities including walking, cycling, and running for 3 minutes each.	The mean error was −1.7 bpm and the MAE was 3.1 bpm. The mean percentage error of −1.3% and a MAPE of 3.1%.
Khushhal et al [27]	Validity and Reliability of the Apple Watch for Measuring Heart Rate	Apple Watch	21	5-min of walking, jogging, and running at speeds of 4,	Very good correlations with the criterion during walking (L: r=0.97; R: r=0.97), but good (L: r=0.93; R: r=0.92) and poor/good (L: r=0.81;

	During Exercise			7 and 10 km/h	R: r=0.86) correlations during jogging and running.
Muller et al [28]	Heart Rate Measures From Wrist-Worn Activity Trackers in a Laboratory and Free-Living Setting: Validation Study	Polar A370, Tempo HR	55	Stationary bicycle for 20 min and a free-living phase during waking hours of the following day	Tempo HR showed a moderate ICC (0.51; 95% CI 0.38 to 0.60) with the data from Polar H10. With a MAE of 15.1 and an MAPE of 13.0%. Polar A370 data also had a moderate but stronger ICC with the Polar H10 (0.73; 95% CI 0.66 to 0.78) with a MAE of 7.3 bpm and an MAPE of 6.4%. On average, both the devices underestimated HR: Tempo HR by 9.7 bpm and Polar A370 by 5.7 bpm.
Sanudo et al [29]	Pilot Study Assessing the Influence of Skin Type on the Heart Rate Measurements Obtained by Photoplethysmography with the Apple Watch	Apple Watch	45	Cycle ergometer at a workload of 50 W for 5 min and a maximal graded exercise test at an initial load of 50, that increased by 25 W every one min until exhaustion	The standard error was 0.15 bpm per min.
Parak et al [30]	Estimating Heart Rate, Energy Expenditure, and Physical Performance	PulseOn	24	Outdoor running test, 5 km distance during at least 20 min	PulseOn estimated HR accurately over the entire protocol, MAPE of 1.9% and reliability 95.4% during a

	With a Wrist Photoplethysmography Device During Running			Treadmill at 8 km/h for 6 min and between 8 and 10 km/h until exhaustion	maximal voluntary exercise test.
Parak et al [31]	Evaluation of wearable consumer heart rate monitors based on photoplethysmography	MioAlpha	21	Sitting, lying, walking, running, cycling, and some daily activities involving hand movements	HR estimation was compared against values from the reference ECG signal. Accuracy against reference was 77.83% for Mio Alpha.
Stove et al [32]	Accuracy of the wearable activity tracker Garmin Forerunner 235 for the assessment of heart rate during rest and activity	Garmin Forerunner 235	29	Cycling at 50 rpm, with a load of 25W, 50W, 100W and 150 W each for 3 min, Treadmill: 4.8, 8.7 12.1 km/h each for 3 minutes. Rapid arm movements with light weight lifting (1 kg for women and 2 kg for men).	Garmin Forerunner 235 had high agreement with the reference device during rest (r = 0.997) cycling at 150 W (Rho = 0.889), treadmill running at 8.7 km/h (r = 0.906) and 12.1 km/h (r = 0.845) and rapid arm movements (r = 0.928, r = 0.745) but a low agreement during cycling at 50 W (Rho = 0.269) and 100W (Rho = 0.462) and treadmill walking at 4.8 km/h (r = 0.481).
Bai et al [33]	Comparative evaluation of heart rate-based monitors:	Apple Watch, Fitbit Charge HR	39	20 minutes of sedentary activity, 25 minutes of aerobic	Fitbit Charge HR MAPE of 7.2% during sedentary behavior phase, 8.4% during aerobic exercise phase

	Apple Watch vs Fitbit Charge HR			exercise, and 25 minutes of light intensity physical activity	and 10.1% during light physical activity phase. Apple Watch: MAPE not obtained.
Reddy et al [34]	Accuracy of Wrist-Worn Activity Monitors During Common Daily Physical Activities and Types of Structured Exercise: Evaluation Study	Fitbit Charge 2, Garmin Vívosmart HR+	20	Treadmill at between 4 and 6 mph, incline was increased by 2% every 2 min until exhaustion Cycle ergometer at 60 rpm, power output was increased every 2 min by 30 W until exhaustion A resistance circuit workout (2 sets of 8 repetition) 28 min of routine activities of daily living, HIIT for 27 min	Garmin Vivosmart HR+ MAPE of 10.79% Fitbit Charge 2 MAPE of 11.33%.
Bordeaux et al [35]	Validity of Wearable Activity Monitors during Cycling and	Apple Watch, Fitbit Blaze, Fitbit Charge 2, Polar	50	Cycling and 3 sets of 4 resistance exercises	The average MAPE in measuring HR during resistance activity of the devices were following: Fitbit Charge 2 9.97%, Fitbit Blaze: 13.74%, TomTom Touch:

	Resistance Exercise	A360, Garmin Vivosmart HR, TomTom Touch			19.14%, Apple Watch 10.99%, Garmin Vivosmart HR: 10.66%, Polar A360: 8.66%. During graded exercise cycling the average MAPE in measuring HR were following: Fitbit Charge 2 21.36%, Fitbit Blaze: 21.06%, TomTom Touch: 12.33%, Apple Watch: 4.14%, Garmin Vivosmart HR: 25.38%, Polar A360: 19.48%.
Cadmus-Bertram et al [36]	The Accuracy of Heart Rate Monitoring by Some Wrist-Worn Activity Trackers	Fitbit Surge, Basis Peak, Fitbit Charge, Mio Fuse	40	Treadmill for 10 min at 65% of the maximum HR	The LoA were relatively poor for all the activity trackers (Mio Fuse, −22.5 to 26.0 bpm; Basis Peak, −27.1 to 29.2 bpm; Fitbit Surge, −34.8 to 39.0 bpm; and Fitbit Charge, −41.0 to 36.0 bpm).
Martin-Escudero et al [37]	Are Activity Wrist-Worn Devices Accurate for Determining Heart Rate during Intense Exercise?	Fitbit Charge, Apple Watch, TomTom Runner Cardio, Samsung G2	8	Treadmill with an incline of 1% at a final speed of 16 km/h or cycle ergometer with a load of 25 W/min until between 250 and 350 W	Apple Watch and TomTom Runner Cardio had the highest correlation for each test. Fitbit Charge HR had a low correlation with R=0.77 in the cycle ergometer test, Samsung G2 had a negative low correlation with R=-0.11, compared with the reference ECG data. All devices showed high sensitivity to motion artifacts and failed to follow accurate HR when the athletes reach

					levels of maximum effort (higher HR).
Chow et al [38]	Accuracy of Optical Heart Rate Sensing Technology in Wearable Fitness Trackers for Young and Older Adults: Validation and Comparison Study	Xiaomi Mi Band 2, Garmin Vivosmart HR +	40	Treadmill: walking, brisk walking/ jogging each for 6 min Cycling for 6 min Elliptical machine exercise for 6 min	For Young group a total MAPE was estimated for 3.77 for Garmin Vivosmart HR+ and 7.69 for Xiaomi Mi Band. For Senior group a total MAPE was estimated for 4.73 for Garmin Vivosmart HR+. and 6.04 for Xiaomi Mi Band.
Duking et al [39]	Wrist-Worn Wearables for Monitoring Heart Rate and Energy Expenditure While Sitting or Performing Light-to-Vigorous Physical Activity: Validation Study	Apple Watch, Polar Vantage V, Garmin Fenix 5, Fitbit Versa	25	Treadmill at 1.1, 1.9, 2.7, 3.6 and 4.1 m/s, each for 5 min Intermittent sprints.	The average sTEE of the values at all different intensities was 0.29 for Apple Watch, 0.52 for Polar Vantage V, 0.86 for Garmin Fenix 5 and 1.26 for Fitbit Versa which corresponds a moderate sTEE for Apple Watch and Polar Vantage V, large sTEE for Garmin Fenix 5 and very large sTEE for Fitbit Versa.
Wang et al [40]	Accuracy of Wrist-Worn Heart Rate Monitors	Fitbit Charge HR, Apple Watch, Mio Alpha, Basis Peak	50	Treadmill at 2, 3, 4, 5, 6 mph each for 3 min	Apple Watch and Mio Fuse exhibited 95% of differences within a range of −27 to +29 bpm relative to the electrocardiogram, the corresponding values for Fitbit Charge HR were within a range of −34 to +39 bpm and for Basis Peak were within a range of −39 to +33 bpm.

Delgado-Gonzalo et al [41]	Evaluation of Accuracy and Reliability of PulseOn Optical Heart Rate Monitoring Device	PulseOn, Garmin Forerunner 610	19	Treadmill At 3, 5, 9 and 11 km/h, each for 3 min Cycling at 60 and 90 rpm, each for 3 min Outdoor activities such as track-running, trail-running, urban-running, walking, track-cycling and road-cycling	The PulseOn had significantly better performance than Garmin Forerunner 610 during the protocol (reliability 94.5% vs 86.6% and accuracy 96.6% vs 94.3%). For the PulseOn mean reliability was 97.8% and accuracy 97.6 % for the outdoor activities.
Thomson et al [43]	Heart rate measures from the Apple Watch, Fitbit Charge HR 2, and electrocardiogram across different exercise intensities	Fitbit Charge HR 2, Apple Watch	30	The Bruce Protocol	CCC was calculated to examine the strength of the relationship between ECG measured HR and HR measured by each device. For both devices, the strongest relationship with ECG-measured HR was found for very light PA with very high CCC (>.90). The strength of the relationship declined as exercise intensity increased for both devices. RER were also calculated to indicate the difference between each device and ECG. The Apple Watch

					showed lower RER (2.4-5.1%) compared with the Fitbit (3.9-13.5%) for all exercise intensities.
Horton et al [44]	Comparison of Polar M600 Optical Heart Rate and ECG Heart Rate during Exercise	Polar M600 Sport Watch	36	Cycle ergometer with a workload of 50-100W for 5 min 21 min of intervals on a cycle ergometer, each stage for 3 min and changed by 25 W. A circuit weight training session with a dumbbell in each hand, each exercise for 30 s Treadmill at 4 and 8 km/h, 3 min stages in the following manner: walk, jog, run, jog, and walk.	Polar M600 a total MAE of 4.8. The agreement of Polar M600 HR and ECG HR was estimated using LoA. The narrowest 95% LoA values were identified for the treadmill interval data (11.3 to −10.7 bpm), while the widest 95% LOA values were observed for the circuit weight training data (27.2 to -39.6 bpm).
Pope et al [45]	Validation of Four Smartwatches in Energy Expenditure and Heart	Apple Watch, Fitbit Surge HR, TomTom Multisport	21	20-min boxing session	Moderate and strong agreement was observed between the chest strap HR monitor and the Apple Watch, Fitbit Surge HR and

	Rate Assessment During Exergaming	Cardio Watch, Microsoft Band			TomTom Multisport Cardio Watch (r=0.47, r=0.73 and r=0.74, respectively).
Benedetto et al [46]	Assessment of the Fitbit Charge 2 for monitoring heart rate	Fitbit Charge 2	15	Stationary cycling with the objective of elevating their heart rate to the greatest extent possible	The mean bias exhibited by the Fitbit Charge 2 in comparison to the ECG was -5.9 bpm. LoA (17 to -29 bmp). ICC between the wrist-worn device and a reference point was 0.21.
Thiebaud et al [47]	Validity of wrist-worn consumer products to measure heart rate and energy expenditure	TomTom Cardio, Microsoft Band Fitbit Surge	20	Treadmill at 3.2, 4.8, 6.4, 8 and 9.7 km/h for 3 minutes at each speed	The MAPE for TomTom Cardio ranged from 1.01 at 3.2 km/h to 7.49 at 4.8 km/h. The MAPE for the Fitbit Surge ranged from -3.35 at 9.7 km/h to 8.06 at 4.8 km/h. For the Microsoft Band, the MAPE varied from 1.31 at 9.7 km/h to 7.37 at 3.2 km/h. The highest correlations with the ECG data were observed at the fastest speeds for the Fitbit Surge (r = 0.84) and TomTom Cardio (r = 0.91), while the highest correlation for the Microsoft Band was observed at 6.4 km/h (r = 0.63).

bpm- beats per minute
CCC- concordance correlation coefficient
ECG- electrocardiogram
HR-heart rate
ICC- intraclass correlation coefficient
LoA-limits of agreement

MAE-mean absolute error
MAPE- mean absolute percent error
RER-relative error rates
RMSE-root mean squared error
sTEE- standardized typical error of the estimate

The study, published in 2017, compared wristbands with chest straps in terms of accuracy of heart rate measurement. 50 volunteers walked and ran on a treadmill. All devices tested were based on the PPG technique, including Mio Alpha, Fitbit Charge HR, Basis Peak, Microsoft Band and TomTom Runner Cardio. The results showed that the wearable activity trackers provided an accurate measurement of heart rate during walking and running activities. The absolute percentage error values varied between 3.3 and 6.2%. It is also interesting to note that the lowest mean absolute percentage error (MAPE) was measured during the final running phase at a speed of 9.6 km/h [19].

In a separate study, 62 participants were required to wear three different wearable heart rate monitors simultaneously during the testing phase. The following devices were the Apple Watch, Fitbit Charge HR, and Garmin Forerunner 225. The subjects were instructed to perform a four-phase exercise protocol on a treadmill, comprising walking at a speed of 2.5 mph, brisk walking at 3.5 mph, and jogging at 5.5 mph, each phase lasting four minutes and followed by a ten-minute seated recovery period. MAPE was calculated for each device. For the Apple Watch was found to be between 1.14% and 6.70%, for the Fitbit device, the HR MAPE was found to range between 2.38% and 16.99% and for the Garmin Forerunner 225, the HR MAPE was found to range between 7.87% and 24.38%. The results obtained from the wearable HR monitors were compared with those from the Polar HR monitor. The correlations between the criterion scores from the Polar heart rate monitor and the readings from the devices indicate the strongest association with the Apple Watch (r=.59-.99), followed by the Fitbit Charge HR (r=.16-.99), and finally the Garmin Forerunner 225 (r=.05-.75). This study found the highest measurement error for all devices in light and moderate physical activity stages [20]. Another study published in Medicine and Science in Sports and Exercise focused on accuracy of wearable heart rate monitors during aerobic exercise. Participants completed exercise protocols on a treadmill, stationary bicycle and elliptical trainer, each of them monitored by a chest strap monitor and two randomly assigned wrist-worn HR monitors. Across all exercise conditions, the chest strap monitor (Polar H7) had the best agreement with ECG, followed by the Apple Watch, the TomTom Spark, and the Garmin Forerunner. Fitbit Blaze was less accurate. On the treadmill, all devices performed well except the Fitbit Blaze. While bicycling, only the Garmin, Apple Watch had acceptable agreement. On the elliptical trainer without arm levers, only the Apple Watch was accurate. None of the devices was accurate during elliptical trainer use with arm levers. In conclusion, it was proven that the accuracy of wearable, optically based HR monitors vary with the type of exercise [21]. Another study conducted in 2019 aimed to assess effectiveness of wrist-worn HR monitors at high levels of exertion. Participants in this study were athletic adults who ran on a treadmill at various speeds. A three-lead ECG and the Polar H7 chest strap monitor were used to accurately assess each subject's heart rate and compare it to the wrist worn monitors. A concordance correlation coefficient was calculated.

Among the devices worn on the wrist, the Apple Watch demonstrated the highest degree of agreement with the ECG (rc= 96). Fitbit Iconic, Garmin Vivosmart HR and Tom Tom Spark 3 all had the same level of agreement (rc= 89). The Apple Watch demonstrated superior performance relative to the other devices. The study showed that the accuracy of all devices decreased during high-intensity exercise, with the Apple Watch III coming closest to the ECG standard. What is also interesting, this study revealed that HR measurements were influenced by BMI and skin color [22]. Another study performed in 2017 assessed the accuracy of seven commercially available wrist-worn devices in estimating heart rate (HR). Evaluated were: Apple Watch, Basis Peak, Fitbit Surge, Microsoft Band, Mio Alpha 2, PulseOn, and Samsung Gear S2. Participants wore devices while sitting, walking, running, and cycling. Devices reported the lowest error for cycling and the highest for walking. Device error was higher for males, greater body mass index, darker skin tone, and walking. Six of the devices achieved a median error for HR below 5% during cycling. The Apple Watch achieved the lowest overall error (1.1-3.9%), while the Samsung Gear S2 reported the highest (4.6-9.0%). The conclusion of this study was that most wrist-worn devices adequately measure HR in laboratory-based activities, although these measurements can still be affected by various factors such as gender, body mass index, skin tone and type of activity performed [23]. Another study aimed to evaluate wrist-worn devices (Apple Watch, Fitbit Charge HR, Samsung Gear S and Mio Alpha) to measure heart rate at rest and during exercise. Participants completed ~1-hour protocols including supine and seated rest, walking and running on a treadmill, and cycling on an ergometer. None of the devices performed significantly better overall. All devices underestimated both outcomes compared with reference methods. The percentage error for heart rate was small for all devices (range: 1-9%). The results suggest that wrist-worn devices using photoplethysmography offer consumers a convenient and satisfactory method of monitoring heart rate during exercise [24]. Another study focused on one specific type of wrist-worn smartwatch, the Garmin Forerunner 225. It was compared with a three-lead patch-based electrocardiogram. The mean values per three minutes of every condition did not differ significantly between the Garmin Forerunner 225 and electrocardiogram [25]. Another study on the effectiveness of smart devices in measuring heart rate found that The Philips Health Watch can provide valuable information by measuring and tracking resting heart rate. All participants performed various daily activities including rest (watching TV), treadmill (4.5 km/h), treadmill uphill 5% (3 km/h), ergometer bike (60 rpm), cross trainer (60 W), household activities and outdoor activities including walking, cycling and running. The MAPE was estimated to be 3.1%. The effectiveness of the watch depended on the type of activity performed, although in this study high intensity activity correlated with worse heart rate measurements [26]. Another study focused on the validation of the Apple Watch. It was compared with a chest HR monitor. Participants performed the following exercises: walking at a speed of 4 km/h, jogging at a speed of 7 km/h and running at a speed of 10 km/h. The study found that the effectiveness of the Apple Watch in measuring heart rate was most reliable during moderate activity such as walking, and that the accuracy of the device deteriorated as the intensity of the exercise increased [27]. In a separate study, the objective was to evaluate the accuracy of a high-cost, customer-based tracker in comparison to a low-cost alternative. The participants were equipped with two smartwatches and a chest-strap heart rate monitor. The devices were tested in a laboratory setting and subsequently during a free-living phase.

The exercise protocol comprised 20 minutes of cycling on a stationary bicycle in a controlled laboratory environment, followed by the measurement of activity during the subsequent day's waking hours in a free-living phase. The findings of this study demonstrated that the low-cost device, Tempo HR, was capable of accurately measuring heart rate with a mean absolute error (MAE) of 15.1 beats per minute (bpm) and a mean absolute percentage error (MAPE) of 13%. In comparison, the high-cost device exhibited a MAE of 7.3 bpm with a MAPE of 6.4% during the laboratory phase. In contrast with the findings of the laboratory phase, during the free-living phase both devices demonstrated an overestimation of HR. The Tempo HR exhibited smaller errors, with a mean absolute error (MAE) of 8.7 bpm and a mean absolute percentage error (MAPE) of 10.2%. In comparison, the data collected from the Polar A370 was comparable to that obtained during the laboratory phase (MAE 5.9 bpm, MAPE 7.1%). In conclusion, the data obtained from the Polar A370 smartwatch demonstrated a high degree of agreement with the data obtained from the chest strap HR monitor, with low measurement errors (below the 10% validity cutoff) in both phases. In contrast, the low-cost device showed only moderate agreement with the chest strap monitor. Furthermore, the study revealed that the discrepancies between the Tempo HR and the Polar H10 were most pronounced at higher heart rates, both in the laboratory and free-living phases. This indicates that the observed measurement errors are predominantly attributable to errors at high heart rates [28]. Additionally, a study has been conducted to evaluate the impact of skin type on heart rate (HR) measurements obtained with the Apple Watch. The participants undertook a graded incremental cycle-ergometer test while wearing the Apple Watch and a Polar chest strap monitor as a criterion measure. It was therefore concluded that the Apple Watch is an accurate means of measuring HR when cycling at different intensities, and that certain types of skin do not exert an influence on these measures. The absolute discrepancy between the measurements obtained and the criterion measurements was less than 2% [29]. In addition to the other physical activities, running was also subjected to testing. The subjects were required to perform an outdoor track run for a minimum of 20 minutes and a treadmill exercise in the laboratory setting at a pace of 8 km per hour for a duration of 6 minutes, followed by a run with an increased speed of 8-10 km per hour until the participant requested to end the exercise. Consequently, the device worn on the wrist was able to estimate the subject's heart rate with precision throughout the entire protocol, even at maximum heart rate and running speeds. The study concluded with the assertion that a heart rate monitoring device worn on the wrist may be employed to accurately estimate heart rate during activities of moderate to medium intensity, with a mean absolute percentage error (MAPE) of 1.9% during a maximal voluntary exercise test [30]. In the study conducted in 2014 a wrist worn HR measuring device, MioAlpha was tested. Twenty-one participants completed an exercise protocol which included sitting, lying, walking, running, cycling, and some daily activities involving hand movements. For comparison purposes, a standard electrocardiogram was employed. The reliability of heart rate estimation was calculated to be 77.83%, with results dependent on the type of activity [31]. The objective of another study was to assess the accuracy of the Garmin Forerunner 235 in relation to different exercises at varying intensities. Twenty-nine participants were asked to perform an exercise protocol which included cycling, treadmill walking, running and rapid arm movement. The cycling was performed with a pedal rate of 50 rpm and a load of 25W, 50W, 100W and 150 W over a period of three minutes.

The treadmill exercise was performed at the following speeds: 4.8 km/h, 8.7 km/h and 12.1 km/h, each for a period of three minutes. The participants were instructed to perform rapid arm movements in conjunction with light weightlifting, with the weight of the weights specified as 1 kg for women and 2 kg for men. For the purposes of comparison, a chest strap monitor was also utilized. The correlation between heart rate measurements obtained from the device worn on the wrist and those recorded by the chest strap monitor was found to be highly significant during treadmill running at an 8.7 km/h pace and rapid arm movements following rest. Significant correlations were observed during cycling with a 150W load, treadmill running at a pace of 12.1 km per hour, and rapid arm movements following exercise. Low correlations were observed during cycling at 100W and treadmill walking at a pace of 4.8 km per hour, with negligible correlations evident during cycling at 50W. The findings of this study also demonstrated that wrist-worn devices are an effective method for measuring heart rate (HR), although they may be subject to influence by the type of physical activity. The sources of error in PPG HR, as identified by the results of this study, may include motion artefacts, misalignment between the skin and optical sensor, variations in skin color, and poor tissue perfusion. However, in this study, these sources of error were only observed in one specific activity, namely cycling with a certain load. It is also noteworthy that as the intensity of physical activity increased, the accuracy of the HR measurement also improved. This may be attributed to the enhanced perfusion that occurs with elevated levels of physical exertion. The results of the rapid arm movement protocol demonstrated a notable reduction in HR measurements during rapid arm movements, indicating that the accuracy of PPG HR measures is dependent on the activity in question. In activities involving minimal arm movement, PPG technology exhibited superior performance. Notwithstanding these limitations, wearable devices with PPG HR sensors have the potential to deliver accurate HR measurements, with the additional benefit of advancing with high usability and comfort [32]. In a further study conducted in 2017, the accuracy of measurements taken by two wrist-worn devices was compared. The Apple Watch and the Fitbit Charge HR were the devices under comparison. A total of 39 participants completed an activity protocol comprising 20 minutes of sedentary activity, 25 minutes of aerobic exercise, and 25 minutes of light-intensity physical activity, including activities such as folding laundry, sweeping, moving light boxes, stretching, or slow walking. The study sample was diverse, with a BMI range of 18.5 to 37.6. The Fitbit Charge HR exhibited a mean absolute percentage error (MAPE) of 7.2% during the sedentary behavior phase, 8.4% during the aerobic exercise phase and 10.1% during the light physical activity phase. A higher correlation was observed between the recorded data and the actual heart rate during the sedentary activity and aerobic segments, in comparison to the light physical activity phase. Furthermore, the device demonstrated a tendency to underestimate heart rate in instances of higher intensity activity and in participants with higher resting heart rates. The mean absolute percentage error (MAPE) of the Apple Watch in measuring heart rate is not provided. In conclusion, the Fitbit Charge HR was described as a novel technique, effectively used as a consumer device [33]. A further study concentrated on a range of physical activities. The participants were requested to undertake a graded maximal aerobic exercise test, which was conducted on a treadmill or cycle ergometer, until volitional exhaustion.

Each participant commenced the test with a five-minute standing rest period, followed by a four-minute warm-up walk at a speed of 3.0 mph and an initial grade of 0%, which was maintained for two minutes before increasing to a grade of 5% for a further two minutes. Following the warm-up period, participants selected a comfortable running speed between 4 and 6 mph. Thereafter, the treadmill incline was increased by 2% every 2 minutes until the participant reached volitional exhaustion. For the cycle ergometer, each participant commenced with a five-minute seated rest period, followed by four minutes of warm-up cycling at a moderate cadence (approximately 50–60 revolutions per minute [rpm]) at zero load. Subsequently, the cycling cadence was maintained at 60 rpm, and the power output was increased every two minutes by 30 watts until the participant reached volitional exhaustion. In the second block of activity on the same day, a resistance circuit workout was performed, comprising two sets of eight repetition maximum exercises for all major muscle groups. Another activity consisted of 28 minutes of routine activities of daily living (ADLs) and high-intensity interval training (HIIT) for 27 minutes, performed on a treadmill or cycle ergometer. In the present study, two devices were subjected to evaluation. The devices under consideration are the Garmin Vívosmart HR+ and the Fitbit Charge 2. The participants were equipped with a chest strap heart rate monitor for the purposes of providing a reference point. The mean absolute percentage error (SD) for the Garmin and Fitbit was 10.79% and 11.33%, respectively. The lowest mean error in measuring HR was observed during the treadmill high-insensitivity protocol (Fitbit: -1.7% [SD 11.5], Garmin: -0.5% [SD 9.4]), whereas the highest error was observed on both the cycle ergometer (Fitbit: -11.4% [SD 35.7], Garmin: -14.3% [SD 20.5]) and the treadmill maximal aerobic exercise test (Fitbit: -16.4% [SD 21.6], Garmin: -9.3% [SD 17.0]). It is noteworthy that the placement of the wrist-worn device emerged as a significant factor influencing the measurements. The error was observed to be higher on the right wrist than on the left wrist for the treadmill maximal aerobic exercise test, treadmill high-insensitivity protocol, and activities of daily living. Conversely, the error was higher on the left wrist than on the right wrist for the resistance and cycle ergometer maximal aerobic exercise tests. It was found that both devices produced erroneous heart rate (HR) measurements during periods of non-wrist use, such as when the devices were stored in a backpack during a commute. The study demonstrated that the accuracy of heart rate (HR) measurements obtained from these activity monitors is acceptable during low-intensity activities and high-intensity activities involving repetitive wrist motion. However, the accuracy of HR measurements is significantly reduced when there is no repetitive wrist motion and when any activity is performed at a high intensity [34]. In a separate investigation, a number of devices were subjected to evaluation. The Apple Watch Series 2, Fitbit Blaze, Fitbit Charge 2, Polar A360, Garmin Vivosmart HR and TomTom Touch were randomly allocated and each participant was required to wear three wrist-worn devices in order to measure their heart rate. The subjects were connected to a six-lead electrocardiogram (ECG) in order to provide a reference for a HR measurement. The participants undertook individual trials of progressive cycling and three sets of four resistance exercises at a load corresponding to their 10-repetition maximum. The MAPE values demonstrated lower levels of error during periods of rest (1.21%–7.56%) and higher levels of error as the intensity of the exercise increased (e.g., 4.40%–16.70% at 0 W; 4.84%–27.75% at 100 W). The Apple Watch demonstrated consistent performance across all levels, maintaining MAPE values below 10%.

The remaining wearable devices exhibited MAPE values of 10% or higher at all or the majority of stages. Compared with ECG, Fitbit Blaze, Fitbit Charge 2 and Garmin Vivosmart HR had values significantly different from the ECG during all stages except from rest. The average MAPE in measuring HR during resistance activity of the devices were following Fitbit Charge 2 9.97%, Fitbit Blaze: 13.74%, TomTom Touch:19.14%, Apple Watch Series 2: 10.99%, Garmin Vivosmart HR: 10.66%, Polar A360: 8.66%. During graded exercise cycling he average MAPE in measuring HR were following Fitbit Charge 2 21.36%, Fitbit Blaze: 21.06%, TomTom Touch:12.33%, Apple Watch Series 2: 4.14%, Garmin Vivosmart HR: 25.38%, Polar A360: 19.48%. Among tested devices, HR accuracy, as reflected by intraclass correlation and MAPE values, was highest in the Apple Watch Series2. The study proved that not all devices are valid for determining HR and the readings may vary during different forms and intensities of physical activity. Moreover, it was found that the higher the exercise intensity during cycling and resistance exercise, the greater the tendency was for most devices to underpredict HR [35]. The objective of another study was to ascertain the precision of heart rate (HR) measurements obtained from four wrist-worn devices. The Fitbit Surge, Fitbit Charge HR, Basis Peak and Mio Fuse were randomly allocated to the 40 participants, with a randomly ordered selection of left or right hand and proximal or distal configuration. The subjects were instructed to perform exercise on the treadmill at 65% of their maximum heart rate. The study demonstrated that the limits of agreement were relatively poor for all the activity trackers (Mio Fuse, −22.5 to 26.0 beats/min; Basis Peak, −27.1 to 29.2 beats/min; Fitbit Surge, −34.8 to 39.0 beats/min; and Fitbit Charge, −41.0 to 36.0 beats/min). All of the trackers demonstrated superior performance during the resting phase in comparison to the exercise phase [36]. Another study aimed to assess the accuracy of heart rate (HR) measurements during intense exercise. Eight participants were subjected to maximal stress testing, which involved either treadmill or cycle ergometer exercise. All athletes exhibited heart rates in excess of 150 beats per minute. The following devices were subjected to testing: Fitbit Charge, Apple Watch, TomTom Runner Cardio, and Samsung G2. For comparison purposes, electrocardiogram (ECG) measurements were also obtained. All devices demonstrated high sensitivity to motion artefacts and failed to accurately track HR when the athletes reached levels of maximum effort (higher HR). The paired mean difference between the ECG and the device result was subjected to analysis. The mean difference for the Fitbit Charge was 11.9, for the TomTom Runner Cardio 1.1, for the Apple Watch 0.3 and for the Samsung G2 62.7. The findings of this study demonstrate that the Apple Watch and TomTom Runner Cardio have a satisfactory degree of accuracy in estimating heart rate, particularly during low-intensity exercises. The Fitbit Charge and Samsung models exhibited significant inaccuracy above 150 bpm. In contrast, the wrist-worn wearables developed by Apple and TomTom exhibited the highest degree of validity for monitoring HR during physical activity at varying intensity levels. It can therefore be concluded that the validity of exercise recommendations based on heart rate measurements obtained from these devices is acceptable. Furthermore, considerable variability and notable discrepancies were evident between the ECG and the device-derived HR measurements across the various HR ranges (less than 110 bpm, from 110 to 150 bpm, and greater than 150 bpm). During exercise performed at the highest intensity, with a heart rate range exceeding 150 beats per minute, the degree of inaccuracy was the greatest, likely due to the presence of a greater quantity of motion artefacts.

The presence of motion artefacts represents a significant challenge in the estimation of heart rate (HR) during periods of intense physical activity [37]. In a separate study, the participants were divided into two age groups: Young (aged 20–26 years) and Senior (aged 65 years and above). In this study, the Garmin Vivosmart HR+ and Xiaomi Mi Band were subjected to testing. A chest HR monitor was used as a reference standard. All participants were required to undertake exercise in six-minute periods, comprising walking on a treadmill, brisk walking or jogging on a treadmill, cycling and exercising on an elliptical machine. For the Young cohort, MAPE was estimated at 3.77 for the walking phase, 2.85 for running, 4.92 for cycling, and 2.52 for exercising on the elliptical machine, with a total MAPE of 3.77 for the Garmin Vivosmart HR+. The estimated MAPE for the Xiaomi Mi Band was 7.46 for the walking phase, 8.32 for running, 10.93 for cycling, and 10.77 for exercising on an elliptical machine, resulting in a total MAPE of 7.69. For the Senior group, MAPE was estimated at 7.06 for the walking phase, 2.54 for running, 3.65 for cycling, and 5.04 for exercising on an elliptical machine, resulting in a total MAPE of 4.73 for the Garmin Vivosmart HR+. For the Xiaomi Mi Band, the MAPE was estimated at 8.69 for the walking phase, 7.02 for running, 3.78 for cycling, and 6.38 for exercising on an elliptical machine, resulting in a total MAPE of 6.04. The mean MAPE values for the Xiaomi device were found to be higher than those for the Garmin device, indicating that the Xiaomi product exhibited lower reliability than the Garmin one. However, the standard deviation of MAPE achieved by the Garmin device was higher in the senior group than in the young group, indicating that age differences may have affected the reliability of the Garmin device, particularly in the older population. In conclusion, the findings of this study indicate that both the Garmin and Xiaomi optical heart rate sensors are capable of producing heart rate readings that are relatively accurate for both young and older adults. The accuracy of the heart rate readings produced by both devices was found to be influenced by the type of physical activity being undertaken [38]. In another investigation, four wearable devices were evaluated. These included: the Apple Watch, Polar Vantage V, Garmin Fenix 5, and Fitbit Versa. In this study, the standard typical error of estimate (sTEE) was calculated. Each participant was monitored while seated as well as during walking and running at varying speeds (1.1 m/s, 1.9 m/s, 2.7 m/s, 3.6 m/s, and 4.1 m/s) for a period of five minutes. Furthermore, all participants were required to complete six 30-meter sprints, which involved multiple changes in direction. The mean sTEE of the recorded values across all intensities was 0.29 for the Apple Watch, 0.52 for the Polar Vantage V, 0.86 for the Garmin Fenix 5 and 1.26 for the Fitbit Versa. This corresponds to a moderate sTEE for the Apple Watch and Polar Vantage V, a large sTEE for the Garmin Fenix 5 and a very large sTEE for the Fitbit Versa. In terms of overall validity, the Apple Watch Series 4 demonstrated the greatest accuracy (with an average deviation of 3.9 bpm from the criterion measure), followed by the Polar Vantage V (7.0 bpm), Garmin Fenix 5 (9.9 bpm), and Fitbit Versa (11.4 bpm). The validity of heart rate monitoring by the Apple Watch Series 4 and Polar Vantage V was found to be less influenced by exercise intensity than that of the Garmin Fenix 5 and Fitbit Versa [39]. In a separate study, 50 subjects were enrolled. Four wearable HR monitors were randomly assigned to the participants, who wore two different wrist-worn HR monitors, standard electrocardiographic limb leads, and a chest strap HR monitor. The participants were instructed to perform a series of exercises on the treadmill at a range of speeds, including 2 mph, 3 mph, 4 mph, 5 mph, and 6 mph, with each exercise lasting three minutes.

The study revealed significant inconsistencies in the accuracy of wrist-worn HR monitors, with none of the devices achieving the precision of a chest strap–based monitor. In general, the accuracy of wrist-worn monitors was optimal at rest and declined with exercise. The Apple Watch and Mio Fuse exhibited 95% of differences within a range of −27 to +29 bpm relative to the electrocardiogram, while the Fitbit Charge HR demonstrated 95% of values within a range of −34 to +39 bpm and the corresponding values for the Basis Peak were within a range of −39 to +33 bpm [40]. In a further study, 19 participants were instructed to complete a series of exercises on a treadmill, including walking and running at varying speeds and at different intensities. The speeds were 3 km/h, 5 km/h, 9 km/h and 11 km/h, and the cycling speeds were 60 and 90 rpm, with each part lasting three minutes. HR signals were acquired with the wrist-worn device Garmin Forerunner 610 and the PulseOn HR monitor, with both devices located on different wrists. The chest-strap ECG monitor was used as a reference. In the study reliability and accuracy of the devices was assessed. Reliability was defined as a % of time that the absolute error is smaller than 10 bpm and accuracy was defined as complement of the relative error. The PulseOn had significantly better performance than Garmin Forerunner 610 during the protocol (reliability 94.5% vs 86.6% and accuracy 96.6% vs 94.3%). Furthermore, participants were randomly assigned to perform physical exercises in an outdoor setting in order to assess HR monitoring devices in real-life conditions. Participants were asked to perform track-running, trail-running, urban-running, walking, track-cycling and road-cycling. For the PulseOn mean reliability was 97.8% and accuracy 97.6 % for the outdoor activities. The results of this study demonstrate that heart rate monitors based on PPG technology can be used in outdoor activities and can be integrated into our daily lives [41]. A further study, conducted in 2019, aimed to compare the accuracy of HR measurements obtained from the Apple Watch and the Fitbit HR 2. The study involved 30 participants, who completed the Bruce Protocol [42] on a treadmill. ECG measurements were used as a reference point for the data obtained from wearable HR monitors. A concordance correlation coefficient (CCC) was calculated to examine the strength of the relationship between the HR measured by ECG and the HR measured by each device. Additionally, relative error rates (RER) were calculated to indicate the discrepancy between each device and the ECG. The Apple Watch exhibited a lower RER (2.4-5.1%) in comparison to the Fitbit (3.9-13.5%) across all exercise intensities. For both devices, the strongest relationship with ECG-measured HR was observed for very light physical activity, with a very high CCC (>.90) and equivalence. As the intensity of the exercise increased, the strength of the relationship between the two devices and the ECG-measured HR declined. These findings suggest that the accuracy of real-time heart rate monitoring by the Apple Watch and Fitbit Charge HR2 is diminished as exercise intensity increases [43]. In a separate investigation, the precision of the Polar M600 wrist-worn heart rate monitor was assessed. A total of 32 participants were enrolled in the study. Subjects performed a 5-min cycle warm-up on a cycle ergometer with a light workload (50–100W), followed by 21 min of intervals on a cycle ergometer. Each stage lasted three minutes and was increased by 25 W. The subjects then performed a circuit weight training session with a dumbbell in each hand. The exercises included shoulder shrugs, squats, bicep curls, and lunges. Each exercise was performed for 30 s with no rest between exercises. The subjects then proceeded to undertake a 15-min interval session on a treadmill, comprising five 3-minute stages, in the following order: walking, jogging, running, jogging, and walking.

The Polar M600 data was then subjected to a MAE calculation. The Polar M600 exhibited a MAE of 4.8 throughout the course of all activities. The highest MAE was observed during the weight training phase (12.7), while the lowest MAE was recorded during the rest phase (1.9). Furthermore, the agreement of the Polar M600 HR and ECG HR among the four exercise phases was estimated using limits of agreement (LOA). The narrowest 95% LOA values were identified for the treadmill interval data (upper LOA, 11.3 bpm; lower LOA, −10.7 bpm), while the widest 95% LOA values were observed for the circuit weight training data (upper LOA, 27.2 bpm; lower LOA, −39.6 bpm). The Polar M600 demonstrated a progressive enhancement in accuracy with the progression of exercise transitions during cycle intervals, coinciding with the elevation of HR to its peak values for this specific cycling activity. In conclusion, the Polar M600 was found to be accurate during periods of steady-state cycling, walking, jogging, and running [44]. In another study 21 participants completed a 20-minute boxing session on the Nintendo Wii. In this study the following wrist-worn devices were tested: the Apple Watch, Fitbit Surge HR, TomTom Multisport Cardio Watch and Microsoft Band. Each participant was equipped with four wrist-worn HR monitors in addition to a chest strap to serve as a reference point for HR measurement. The intraclass correlation coefficients were calculated in order to determine the extent of agreement between the average heart rate measurements recorded by each smartwatch and those obtained from the chest strap heart rate monitor. Moderate and strong agreement was observed between the chest strap HR monitor and the Apple Watch, Fitbit Surge HR and TomTom Multisport Cardio Watch (r=0.47, r=0.73 and r=0.74, respectively) [45]. In a separate study, the accuracy of the Fitbit Charge 2 for monitoring heart rate was evaluated in comparison to an electrocardiogram (ECG) criterion measure. Fifteen participants were instructed to engage in stationary cycling with the objective of elevating their heart rate to the greatest extent possible. The mean bias exhibited by the Fitbit Charge 2 in comparison to the ECG was -5.9 bpm. Additionally, the limits of agreement (LoA) were calculated, with the upper LoA being +17 bpm and the lower LoA being -29 bpm. The intraclass correlation coefficient (ICC) between the wrist-worn device and a reference point was 0.21. The study concluded that the Fitbit Charge 2 tends to underestimate the heart rate, with a consistent bias and lack of precision across the range of heart rates [46]. In a further investigation, 20 participants engaged in treadmill exercise at speeds of 3.2, 4.8, 6.4, 8 and 9.7 km/h for a period of three minutes at each speed. Each subject was instructed to wear two wrist-worn monitors to measure their heart rate; these were randomly assigned from the TomTom Cardio, Microsoft Band and Fitbit Surge. A three-lead electrocardiogram was used as a reference point. For each device, MAPE was calculated for each speed. The MAPE for the TomTom Cardio device exhibited a range from 1.01 at 3.2 km/h to 7.49 at 4.8 km/h. The MAPE for the Fitbit Surge exhibited a range of -3.35 at 9.7 km/h to 8.06 at 4.8 km/h. For the Microsoft Band, the MAPE varied from 1.31 at 9.7 km/h to 7.37 at 3.2 km/h. The accuracy of heart rates derived from the wrist-worn monitors was calculated in relation to the ECG readings. The highest correlations were observed at the fastest speeds for the Fitbit Surge (r = 0.84) and TomTom Cardio (r = 0.91), while the highest correlation for the Microsoft Band was observed at 6.4 km/h (r = 0.63). In general, it can be observed that the higher the heart rate resulting from an increase in speed, the greater the accuracy of the devices in question [47].

DISCUSSION

The studies analyzed in this document reveal significant insights into the accuracy of wrist-worn heart rate monitors. While the convenience and usability of these devices are clear, the results demonstrate that there are notable limitations in their ability to provide consistent and reliable heart rate data. It should be noted that the studies included in this review are subject to certain limitations. These include the use of small groups of participants, the inclusion of only healthy individuals in heterogenous groups, the limitation of studies to laboratory-controlled conditions, and the potential for bias due to funding sources, namely the involvement of wearable device producers. The contradictory findings of the studies referenced in this review, including the accuracy of wearable devices across all forms of physical activity, reinforce the necessity for further research with larger sample sizes.

The importance of valid measurements of HR is hard to estimate as it influences the way how people perceive their physical health and their sport habits. According to Takacs, inaccurate measures of physical activity can affect the ability to monitor health status and are potentially dangerous for users. HR training relies in fact on exercising in different HR zones, each of which is a percentage of your maximum HR: once these are calculated, the workout can be tailored to the specific user, balancing fitness gain without overloading the heart activity [47]. The gaining popularity of wearable devices and the fact that heart rate feedback has been found to increase overall activity and percentage of time spent being vigorously active [48,49] underlines how much the further research is needed.

CONCLUSION

In conclusion wrist-worn devices, while generally accurate for moderate-intensity activities like walking and running, tend to be less accurate for certain exercises such as cycling or elliptical training. Specifically, devices like the Apple Watch consistently performed well across different activities, while others, such as Fitbit Blaze, exhibited significant errors. Across multiple studies, the Apple Watch demonstrated the highest accuracy for heart rate monitoring, with strong correlations to ECG and chest strap results. Other devices, like the Fitbit Charge HR and Garmin Forerunner, showed greater variability and higher error rates, particularly during high-intensity or light activities. A number of factors seems to have an influence on the measurements delivered by wearable devices including BMI, skin color, sex and type of performed activity.

Author's contribution

Conceptualization, KP; methodology, KP, ZS, OB; software, MK, AK, KR, OK, MS; check, ZS, AN; formal analysis, JK, OB, MK; investigation, AN, KR, OK; resources, MS, ZS, KP; data curation, AK, KR; writing – rough preparation, KP, JK, OB; writing-review and editing, AN, ZS; visualization, MK; supervision, ZS, KP; project administration, MS

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