

INNOVATION

Validation of photoplethysmography as a method to detect heart rate during rest and exercise

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Abstract

Despite their enhanced marketplace visibility, validity of wearable photoplethysmographic heart rate monitoring is scarce. Forty-seven healthy participants performed seven, 6-min exercise bouts and completed a valid skin type scale. Participants wore an Omron HR500U (OHR) and a Mio Alpha (MA), two commercial wearable photoplethysmographic heart rate monitors. Data were compared to a Polar RS800CX (PRS). Means and error were calculated between devices using minutes 2–5. Compared to PRS, MA data was significantly different in walking, biking (2.41 ± 3.99 bpm and 3.26 ± 11.38 bpm, $p < 0.05$) and weight lifting (23.30 ± 31.94 bpm, $p < 0.01$). OHR differed from PRS in walking (4.95 ± 7.53 bpm, $p < 0.05$) and weight lifting (4.67 ± 8.95 bpm, $p < 0.05$). MA during elliptical, stair climbing and biking conditions demonstrated a strong correlation between jogging speed and error ($r = 0.55$, $p < 0.0001$), and showed differences in participants with less photosensitive skin.

Keywords

Exercise, fitness, heart rate monitors, photoplethysmography, wearable technology

History

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1. Introduction

Physical inactivity is associated with the precipitous rise of chronic illnesses such as obesity, type II diabetes, heart disease and cancer [1–3]. In 2012, among civilian, non-institutionalized US adults, approximately half (49.8% or 117 million) had at least one of the chronic conditions mentioned above [4]. Such chronic conditions account for \$3 of every \$4 spent on healthcare which, at nearly \$7900 for every American with a chronic disease, costs the US over 500 billion dollars annually [5,6].

In an attempt to address this issue, technologies are emerging designed to measure daily levels of exercise and physical activity. Recently, several devices, collectively known as “wearable technology”, have become commercially available. These include devices worn on the finger or the ear and devices worn on the wrist such as advanced monitoring watches and wrist-bands. Wrist-wear (watches, bands and bracelets) accounted for the largest market share in 2012, netting ~\$850 million that year alone [7].

Wearables, due to their ease of use, non-invasive design and convenience, provide a means of tracking activity with low user burden. Additionally, features such as feedback systems and social networking capabilities are often included

to aid the user in adhering to physical activity regimens and, thus, wearable technology has become an increasingly common method for people to collect data on their own physical activity.

To date several companies have produced commercially available wearable technology, with the majority of these devices collecting data on activity in the form of steps taken and estimated energy expenditure with the use of piezo-electric accelerometers and/or geographical positioning systems (GPS). Combining the use of accelerometers with GPS technology that can detect changes in topography better predicted walking speed, from which energy expenditure can be derived [8]. These technologies can also acquire information on activity intensity and total activity volume.

Prior studies examining accelerometer-based wearable technology have shown these devices to be reliable and valid in both children [9–11] and adults [10,12,13]. However, these studies primarily investigated devices worn at the hip and had several limitations, the most important of which is the inability to measure activity levels not associated with step-like motion such as isometric exercise, carrying loads or arm swing. Data also indicate that these devices have demonstrated inaccuracies when walking or running on an incline [14]. Newer designs have begun to address some of these issues by including elements like altimeters in their design. Altimeters use pressure sensors to detect changes in air pressure and weather in reference to a known altitude.

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However, little data has been published as to the validity of such advances in activity tracking devices [15].

To address these limitations and more accurately capture physical activity intensity and frequency, some devices have been developed that include a heart rate monitor. Measuring heart rate works well in combination with accelerometry, as the measurement error of these two approaches is not positively correlated, resulting in more accurate measures of overall activity [16,17].

In addition to steps taken or distance travelled, heart rate provides an essential physiological variable that is associated with activity intensity and can act as a surrogate for energy consumption. Finally, it may be possible to predict future cardiac events and even mortality in both healthy and clinical populations using such technologies [18–20].

Early studies on proof-of-concept versions of devices that were not yet commercially available show that accelerometry combined with heart rate data improves estimates of energy consumption and expenditure [21–23]. More recent studies of devices currently in the marketplace support this, also finding that accelerometry combined with heart rate data provides reasonable estimates of energy expenditure in both children [24] and adults [25]. Others have shown these devices to be valid while walking, running on a treadmill or performing a variety of low-to-moderate level activities such as treadmill and field-based activities [26]. Similarly, our lab reported that there is strong validity and reliability of such devices when examining free-living tasks including walking and jogging [27]. In contrast, findings from others who compared devices that incorporate accelerometry and heart rate to accelerometer-only devices [28] suggest that the combined devices did not provide significantly improved energy estimates compared to single-technology based systems [26,28].

Historically, mobile measures of heart rate were acquired via a chest strap or through using electrodes adhered to the chest. One such device, the Polar heart rate monitor (Polar Electro, Inc., Lake Success, NY), employs a chest strap to detect heart rate and uses a wrist-watch receiver via radio transmission. Wireless transmission between the transmitter and the wrist unit is based on an electromagnetic field. The conventional Polar transmitter (5 kHz devices) transmits a coded time stamp to the receiver in the wrist unit every time it detects a QRS complex, the electrocardiographic (ECG) waveform defined by the contraction of the heart's left ventricle. The code is agreed between the transmitter and the receiver when exercise mode is started. The code ensures that the receiver does not pick up signals from a neighbour's transmitter.

The polar technology of wireless transmission, introduced in 1984, was reported to be valid with Holter ECG reference values in 20 subjects during exercise and was found to be a valid alternative for measuring heart rate in the field and during laboratory tasks [29]. Leger and Thivierge [30] compared the validity of 13 heart rate monitors and found the Polar PE 3000 technology to correlate well with ECG readings ($r > 0.93$), as well as demonstrate a standard error of $< 6.8\%$. Later, Goodsen et al. [31] found the Polar monitor to be within 6 beats of ECG readings during such activities as rowing, arm-leg cycle ergometry and weight training. When heart rate values were averaged every 10 s in women

during walking, jogging and aerobic dance, the Polar monitor was found to have a strong correlation coefficient ($r = 0.99$) with that of an ECG, with 90% of the errors ± 8 beats per minute [32]. The polar monitor technology has been shown to be a valid gold standard of mobile heart rate monitoring technology when compared with ECG measurements during rest [33], exercise [29,31,34] and in laboratory and field environments [29]. Although the Polar heart rate monitor is non-invasive in nature and is shown to be a gold standard instrument, it can be inconvenient to use and may cause minor discomfort when worn for extended periods. In addition, the Polar chest strap needs to be worn on the skin and kept wet for accurate signal detection. This may require the addition of an electro gel for conductance.

Other devices such as the Actiheart[®] (CamNtech Ltd, Cambridge, UK; or Metrisense, Bend, OR) use two electrodes placed under the left collarbone on which a transmitter and data storage unit are attached. These processes are burdensome for reasons beyond the complexity of application, including issues of skin sensitivity and individual physical factors such chest hair which, when abundant, can lead to faulty or incomplete recordings.

To address these issues, new technologies that are less invasive and more convenient are being developed for commercial use. One such device, the Omron HR500U (Omron Healthcare, Inc., Schaumburg, IL), consists of a wristwatch design that uses a non-invasive photoplethysmography (PPG) technique, which has been employed in clinical applications and has been commercially available in pulse oximeters, vascular diagnostic tools and beat-to-beat blood pressure devices for the past four decades. PPG is an optical measurement technique that can be used to detect blood volume changes in the microvascular bed of tissue [35]. Similar to a pulse oximeter, which senses blood flow via light refraction at the arterial level of the fingertip, the Omron device is designed to sense light refraction from the capillaries in the wrist. Heart rate is determined based on the theory that blood flow through the vessel is inversely proportional to the amount of light refracted. To date there are only a few manufacturers that have a wrist-watch device on the market which utilizes this technique to determine heart rate.

Despite their global popularity, convenience and non-invasive approach, wearable sensing technologies have been thrust into the marketplace without appropriate evidence as to their validity and reliability. As new commercial devices are introduced into the market, data supporting the accuracy of wearables may go a long way toward having these devices accepted for intervention programmes that address current epidemics of obesity, diabetes and other chronic disease.

Therefore, a clear understanding of the validity of these wearable devices is essential to understand their usefulness and to calibrate appropriate dose–response relationships between physical activity and health in specific populations. The purpose of this study was to determine the validity of the Omron HR500U when measuring heart rate across a range of physical tasks and compare it to a device using similar technology, the Mio Alpha (Physical Enterprises, Inc., Vancouver, BC, Canada). Both of these commercial technologies were compared against the Polar device technology

which employed a chest strap and has been shown to be highly correlated to electrocardiograph measurements [30–33].

2. Methods

We recruited 50 adult participants in good health to participate in this study. Data used for the analysis shown in this paper was collected from 47 participants (Males; 27, Females; 20); one participant was unable to finish the protocol and two participants were removed from the study due to incomplete data that came from partial device failures. The failures were due to poor conductivity of the chest strap owed to two participants' chest wall size and upper body obesity. This may have an impact on how these devices are best used and on whom and for what body type they are most appropriate. Upper body obesity may push the belt downward and not allow for a strong contact with the skin, eventually leading to poor data acquisition. Participant characteristics are provided in Table 1. The study was conducted at the Health and Wellness Institute at Long Island University Brooklyn, and volunteers were recruited via flyer. Participants were eligible if they were between the ages of 18 and 50, and did not have any history of injury or disease that would prevent them from safely performing the study protocol. The study was approved by the Institutional Review Board of Long Island University Brooklyn.

2.1. Procedures

Participants were required to complete a demographics and health questionnaire, which included a skin type scale (Fitzpatrick Skin Scale[®]) prior to enrolment in the study and were instructed to remove any topical lotions or creams before the study began. Participants then provided informed consent and were instructed on the protocol. To begin, each participant was outfitted with the following: A Polar RS800CX (Polar Electro, Inc., Lake Success, NY), whereby the chest strap was applied as per manufacturer's instructions. Signa Gel (Parker Labs, Fairfield, NJ) was applied to the back of the strap for improved conductance; an Omron HR500U was placed on the left wrist, with a small mother board affixed to the left arm via an elastic arm band to aid data collection. In addition, a Mio Alpha was placed on the right wrist with an accompanying iPod touch (Apple, Inc., Cupertino, CA) for Bluetooth enabled data collection on the right arm above the anticubital fold.

The Omron HR500U device enables continuous heart rate measurement during exercise by an optical sensor and noise removal algorithm. The optical pulse sensor module is equipped to detect a pulse wave caused by capillary blood

flow. The optical sensor uses a green light (wavelength of 530 nm) that is less affected by motion artifact and that has a high absorption coefficient of hemoglobin in blood. Light intensity of the optical sensor is controlled automatically to decrease measurement variability caused by the amount of melanin and body fat. The signal processing algorithm measures heart rate continuously during exercise by removing the motion artifact. Information on the specific algorithm of the MioAlpha was not available at the time this study was conducted. The Polar, Omron and Mio Alpha devices collected data in 5-s epochs, which were used to calculate the average heart rate over each minute while performing the study tasks.

In addition to the three devices, participants were outfitted with a telemetric gas analysis system (K4b² Cosmed Inc., Rome, Italy) comprised of a metabolic analyser, battery pack and face-mask. The K4b² was used to determine the validity of energy expenditure [36,37] data collected from the HR500U, which will be presented in a future publication. Device set up is depicted in Figure 1.

After the devices were properly applied, each participant performed seven distinct activities for a total of 6 min each, with an additional 1 min of rest between each task, as 1-min has been shown to be a sufficient period to detect changes in heart rate recovery after a submaximal exercise bout [27]. The tasks, presented in experimental order, were as follows:



Figure 1. Participant outfitted with the K4b² (centre and face), the Mio Alpha and iPod touch[®] (right wrist and right arm), the Polar RS800CX (right arm); chest strap at level of xiphoid process, underneath K4b² elastic strap) and the Omron HR500U (left wrist).

Table 1. Participant characteristics.

	<i>n</i> (SD)
Age (years)	28.4 (10.1)
Height (cm)	173.0 (9.4)
Weight (Kg)	73.4 (14.2)
Moderate activity (days/week)	4.7 (1.6)
Vigorous activity (days/week)	3.9 (1.8)
Fitzpatrick skin type	3.0 (0.7)

Table 2. Mean activity intensities.

Activity	Mean (SD)
TM Walk (mph)	2.7 (0.6)
TM Walk (grade)	0.3 (1.4)
TM Jog (mph)	5.3 (1.1)
TM Jog (grade)	0.2 (0.5)
Elliptical (Resistance)	6.3 (3.4)
Stairmaster (steps/min)	56.6 (13.2)
Stationary bike (watts)	86.3 (31.4)
Moderate activity (days/week)	4.7 (1.6)
Vigorous activity (days/week)	3.9 (1.8)

TM, Treadmill; mph, miles per hour.

resting (sitting reading a book), treadmill walking, treadmill jogging, elliptical exercise, stair climbing, stationary cycling and light weight lifting composed of a small barbell (1 kg for women and 2 kg for men). Light weight lifting consisted of moving the arms into a biceps curl position then to a bilateral “press” over the head and then returning to the start position. Participants completed one cycle of weight lifting per beat to the sound of a metronome set at 40 beats per minute. Exercise intensity during all activities with the exception of light weight lifting was self-selected, meaning that, within the first minute of each task, each participant was asked to find a pace that allowed them to endure that level of activity for a minimum of 6 min. Mean intensities for each task are listed in Table 2. Participants were instructed to provide feedback regarding their comfort while performing the activities and to let the tester know if they felt any discomfort, fatigue or shortness of breath.

Data was averaged to 5 s epochs after testing was completed. Based on 5-s intervals of data collection, values from the Polar, HR500U and Mio Alpha were synchronized to directly compare data from all devices.

3. Results

Mean values and error as compared to the Polar were calculated using minutes 2, 3, 4 and 5 for each of the seven activities (rest, walking, jogging, elliptical, stairs, bike and weights). Minutes 1 and 6 were eliminated from the analysis as they were not considered as steady state data, but rather reflected a transition from one activity to another.

Specifically, the mean heart rate for each device was calculated at each minute of activity, as determined by averaging over a set of twelve 5-s epochs. Absolute values of the difference scores between the HR500U and Mio Alpha at each minute were then computed. The absolute values of the difference scores represent the error in detecting heart rate for each device (referred to henceforth as error), with lower scores indicating lower measurement error.

A repeated-measures *t*-test compared the average error across all activities for the two devices. Significantly more error was observed across all tasks for the Mio Alpha ($M=6.7$) compared to the HR500U ($M=4.0$), $t(42)=0.26$, $p<0.05$. Examining the error separately for each type of activity (see Table 3) showed that the greatest discrepancy between the two devices occurred during light weight lifting, where the error for the Mio Alpha ($M=23.3$) was more than 4-times greater than that of the HR500U ($M=4.7$),

Table 3. Error and standard error by device and task.

	Mio Alpha	HR 500U
Rest	2.39 ± 6.28	2.22 ± 3.67 ^{b*}
Walking	2.41 ± 3.99 ^{c*}	4.95 ± 7.53 ^{b**}
Jogging	4.97 ± 11.95	5.71 ± 13.30
Elliptical	3.29 ± 10.65	2.11 ± 5.18
Stair Climbing	3.34 ± 11.22	1.66 ± 5.10
Bike	3.26 ± 11.38 ^{c**}	1.00 ± 2.56
Weights	23.30 ± 31.94 ^{a**}	4.67 ± 8.95 ^{c*}

Values = Means ± SE (bpm). Significance indicators are as follows: ^aPolar vs Mio Alpha, ^bPolar vs HR500U, ^cMio Alpha vs HR500U. * $p<0.05$, ** $p<0.01$.

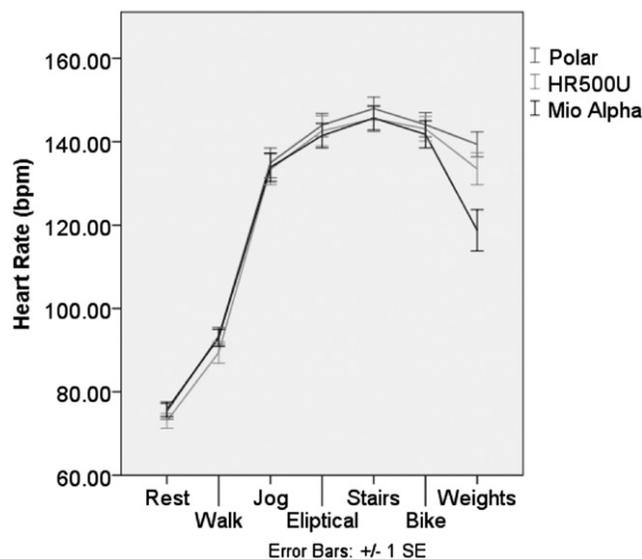


Figure 2. Mean heart rate by activity.

$t(42)=4.1$, $p<0.05$. In the light weight lifting condition, the Mio Alpha consistently under-estimated the heart rate as measured by both the Polar and the HR500U (see Figure 2). Data is unclear as to why this was the case with the Mio Alpha and not the Omron HR500U, even though both devices were fastened in accordance with manufacturer’s instructions using a similar wristwatch-like strap. We speculate it could be due to the motion required of the wrist during the light weight lifting task, resulting in a contact differential and overall greater distance between the photoplethysmograph and the skin. These data suggest that future research of this nature include a measurement of device proximity to the wrist. Discrepancy may also be owed to the light wavelength used in each device and how they detect heart rate in participants with varied skin types [38]. These concerns will be addressed in the discussion section.

In addition to the average error in measuring heart rate, we also examined the variability of the error. To measure error variability we first, as above, took the difference scores. We then calculated the standard deviation of the error across all participants for each device. As can be seen in Table 3, more than twice as much variability was observed for the Mio Alpha compared to the HR500U device during elliptical, stair climbing and stationary bike conditions, while the opposite was observed in the walking condition, where approximately

twice as much error was observed for the HR500U device. Average error between each device and the Polar, as shown in Figure 2, may conceal error variance that gets averaged out across trials, which is made clear in Table 3.

Further examination of the data revealed that heart rate measurement error tends to increase with the intensity of the activity measured and that the strength of this association depends on the type of activity and the device. This is to be expected since, when motion is increased, there is greater disturbance to the blood–sensor interface. Specifically, there is an $r(42) = 0.55$ ($p < 0.0001$) correlation between jogging speed and error for the Mio Alpha, indicating that the error in the Mio Alpha increases as does jogging speed. This correlation is not significant for the Omron device, $r(42) = 0.23$, $p > 0.05$ during jogging. However, during the stair climbing and stationary biking conditions, the error rates of both the HR500U and the Mio Alpha significantly increased with greater speed (HR500U: stairs $r = 0.45$, $p = 0.002$; bike $r = 0.38$, $p = 0.011$, MIO: stairs $r = 0.43$, $p = 0.004$; bike $r = 0.37$, $p = 0.013$).

Finally, since the photoplethysmograph technique can be influenced by skin photosensitivity, we examined photosensitivity as it related to observed error. Photosensitivity was measured by the Fitzpatrick Skin Scale[®], where the range consisted from type 1 = high photosensitivity to type 6 = low photosensitivity. No participants with type 1 or type 6 skin photosensitivity participated in the study, thus only participants with skin types 2–5 were included in the analysis.

A 2×4 mixed design ANOVA, with skin type as a between-subject factor and device as a within-subject factor, was utilized to examine whether the heart rate measurement error was different among the two devices, depending on the skin type, across all conditions. A significant effect of device was observed, as mentioned above. A device \times skin type interaction was also significant, $F(4, 39) = 2.6$, $p < 0.05$, indicating that some skin types produce more error in the Mio Alpha compared to the HR500U.

We next tested a model of a linear interaction (moderation) between skin type and device type. Specifically, we tested the hypothesis that the error increases linearly as a function of skin type at a greater rate for the Mio Alpha device compared with the HR500U. A regression model in which the Fitzpatrick Skin type was entered as the criterion variable, the error as the outcome variable and the device as the moderating variable showed a significant moderation by device of skin type on error (R^2 from interaction = 4.7, $p < 0.05$). Probing the interaction separately for each device, the regression significantly predicted error for the Mio Alpha device ($B = 3.4$, $p < 0.01$), but not for the HR500U device ($B = 0.07$, $p = 0.94$). This result shows that error rate increases linearly with less photosensitive skin for the Mio Alpha, but not for HR500U.

4. Discussion

The data suggest that, when examining average error across activities, the HR500U and Mio Alpha were comparable against the criterion. However, extreme variability around the average observed error showed the Mio Alpha significantly differed when compared to the HR500U. This held true across

several activities, but was most notable in the light-weight lifting condition where the standard deviation of measurement in the Mio Alpha was a sizeable 23.3 beats per minute. Further, the Mio Alpha did not perform as well as speed or intensity was increased and data show it has difficulty detecting heart rate in participants with less photosensitive skin.

The method of PPG to detect heart rate is used in a handful of commercial devices; however, scarce data exist as to whether these devices are accurate. The majority of published data is focused on telemeterized devices that detect heart rate via a chest strap, which has been shown to be a reliable method of determining rate during rest and exercise against that of an electrocardiogram [30–33]. One study found that detection of heart rate via a telemeterized microprocessor during low, moderate, high and maximal intensities resulted in a correlation coefficient of 0.998 to 0.999 as compared heart rate recorded by electrocardiograph [34].

Although data is lacking, there have been studies validating devices that do not require telemeterization. Lea and Gorelick [39] conducted a validation study on a smart watch in which participants were not required to wear a telemetric strap or patch electrodes. In that study they found that the device provided valid heart rates during rest, treadmill walking and light jogging, but, similar to the Mio Alpha device in the current study, the device in that study showed greater error when treadmill speeds were increased. This may be due to a greater disturbance of the blood–sensor interface or it could be owed to the sensitivity of the device, the distance of the device from the skin or the skin type of the participant being studied. This is an area that begs further investigation to tease out the success of these devices as intensities are normally increased and decreased throughout an exercise regimen. Additionally, activities employed in the current study may have illuminated error not seen in previous studies. In the current study the greatest error was seen in activities such as stair climbing, stationary cycling and light weight lifting, activities not examined in previous work [39]. This may be significant as several devices designed to non-invasively detect heart rate are promoted as training tools to enhance exercise programming, in which weight training is often included.

There may be additional reasons as to why light weight lifting demonstrated the greatest error. During weight training, there is often a change or deviation in the wrist position from that of neutral to extension. During stair climbing or stationary cycling the same holds true (albeit to a lesser extent) as participants try to maintain their balance. A change in wrist position may alter the position of the photoplethysmograph, interfering with accurate data collection. For example, while holding on to handlebars such as in the biking condition, muscles isometrically contract. In this manner, muscles generate force without a change in the joint position, creating isometric tension in the forearm. This may change the proximity of the device on the wrist and, therefore, may alter the position of the sensor.

We speculate that this may have contributed to the significant error in the Mio Alpha during these activities. It is important to note that, although the Mio Alpha and HR500U are designed with the same technology and despite

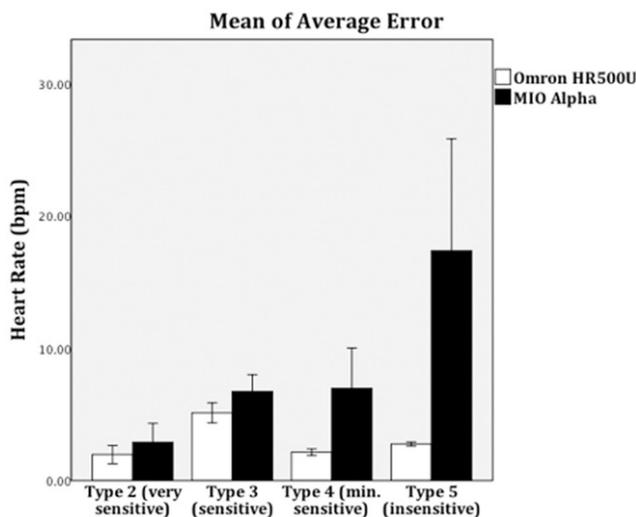


Figure 3. Fitzpatrick Skin Scale[®] data as compared to observed error for all activities.

the fact that both watch devices were snugly adhered to participants' wrists as per manufacturer's instructions, the design of the wrist strap differs between devices. The Mio Alpha incorporates a three-pronged fastener, whereas the Omron HR500U is fastened with a widened one-prong design. Since the HR500U was significantly more accurate during the weight lifting activity, an activity that may involve flexion, extension and deviation of the wrist, researchers in this field may want to investigate strap design as a contributing factor to measurement accuracy during weight lifting tasks.

Finally, photoplethysmography, which uses light refraction as an indicator of blood flow, dictates that the sensitivity of the sensor can be influenced by skin pigment. Although this would seem to be an obvious area of scrutiny of such devices, data on the accuracy of instantaneous heart rate in people of varied skin pigment using a photoplethysmograph is scarce. These current data agree with Fallow et al. [38], who found that green light wavelengths of 530 nm demonstrated the greatest modulation compared to all other wavelengths tested in resting and exercise conditions, regardless of skin type.

Our study is unique in that it presents data that reflects the accuracy of selected photoplethysmograph technologies in adult participants with a range of skin sensitivities while performing a variety of large muscle group exercises. The current data show that the HR500U performed better than the Mio Alpha in participants with lower skin sensitivity (Figure 3), suggesting that the Mio Alpha photoplethysmograph mechanism may not be robust enough to penetrate the skin of individuals with darker skin. More research needs to be done to determine the proper level of sensor sensitivity to detect accurate heart rates while exercising across a range of user demographics.

The information provided by this study may be useful to researchers attempting to make practical decisions regarding the selection of strapless heart rate monitor devices or devices that use advanced detection technology such as photoplethysmography. Perhaps most importantly, researchers must clearly consider the specific activities being examined so the aims of the study can be aligned with the appropriate choice of measurement device. This study suggests that devices that

rely on heart rate detection through the skin may be inaccurate if speed or intensity is increased and during activities where skin contact is lost or if an isometric contraction is necessary to perform the activity.

In addition, the use of heart rate monitoring has played an integral role as a training tool for over 4 decades. Historically, there has been a financial burden associated with expensive equipment and cumbersome attachments. Even monitors that are considered user-friendly and affordable and which have been validated at rest and during various levels and types of physical activity [31,32,40] may still prove difficult to use. They often require a chest strap that may not be appropriate for individuals with sensitive skin, are prone to electrical interference and must be saturated to record heart rate accurately.

The two devices which were the focus of this investigation were both designed with a photoplethysmograph, an innovative mobile health technology found in only a few devices available on the commercial market today. There is a scarcity of research focused on devices that employ photoplethysmography and currently there is only anecdotal evidence that suggest that these devices vary in their ability to determine heart rates accurately at rest and during activity.

Despite the lack of evidence to support their claims, companies continue to produce and sell these monitors as technological advances to promote fitness and health. Therefore, as the technology of wearable devices advances, it behooves the scientific community to test these devices and hold them to a higher standard. To our knowledge this is one of very few studies that focuses on testing the validity of photoplethysmography as a component of a wrist-worn heart rate monitor.

Although this investigation may provide needed information about new wearable technology, there were some limitations. The sample size was small ($n = 47$) and a limited age range of people were tested (19–50 years). We were not able to recruit participants based on skin photosensitivity and, thus, were not able to get a balanced sample within the more extreme skin sensitivities, as designated by the Fitzpatrick Skin Scale[®].

5. Conclusion

The current study showed that, on average, both the HR500U and the Mio Alpha are accurate in detecting heart rate during the majority of activities performed. However, the HR500U provided significantly more accurate data than the Mio Alpha during activities in which intensity (e.g. speed) was higher and for those participants with less photosensitive skin. Additionally, when examining the error of each activity segment, both devices under-performed as compared to the criterion during resting, biking and light weight lifting. More research needs to be conducted to ensure that new technology is validated before coming to market. It is also imperative that photoplethysmographic technology accounts for a variety of skin sensitivities.

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Declaration of interest

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