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Brief Report

A Pilot Study Examining the Convergent Validity of Two Commercially Available Heart Rate Monitoring Devices During Swimming of Different Intensities and Strokes

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Abstract

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The purpose of this study was to determine the feasibility of heart rate (HR) monitoring using an optical monitor (OHR) across different swimming strokes and intensities. Nineteen collegiate swimmers (7M, 12F) completed two swimming protocols (P1: nine 75m freestyle swims at three intensities, P2: two 100m swims using their preferred stroke). During P1, four swimming bouts were completed at light intensity (HR 145-155 beats per minute [bpm]), three at moderate intensity (HR 155-170bpm) and two at vigorous intensity (HR > 170bpm). During P2, participants completing one swimming bout using their preferred stroke (freestyle [n=7], backstroke [n=5], breast stroke [n=4], and butterfly [n=3]) at moderate intensity and one vigorous intensity with one-minute rest between each swim. A repeated measures ANOVA (RM ANOVA) with post hoc analysis was completed between the OHR and a traditional chest monitor (THR) with significance set at $p<0.05$. There was an overall significant difference between mean OHR and THR (OHR: 150.7 ± 17.0 vs. THR: 155.9 ± 19.0 bpm, $p=0.02$) and significant differences during the recovery stage between P1 and P2 (OHR: 126.1 ± 17.8 vs. THR: 122.3 ± 18.0 bpm, $p=0.007$) and the first 100m swim of P2 (OHR: 148.3 ± 21.3 vs. THR: 159.1 ± 20.1 bpm, $p=0.002$). The OHR monitor captured 99.9 ± 0.1% of the HR data whereas the THR captured only 58.98 ± 31.3% of the participants' HR data. The OHR significantly underestimated HR compared to the THR but more consistently captured HR than the THR throughout the duration of the swim test.

Keywords: Optical, device, exercise

Introduction

Wearable technology has evolved rapidly in the past decade. Modern devices are primarily wrist-worn and report numerous physiologic variables such as heart rate (HR), sleep quality, caloric expenditure, and recovery from exercise. Due to their utility, these devices are increasingly popular among coaches and athletes for use during training and recovery.[1,2] However, independent validation of commercially available wearable devices remains inconsistent, with many devices relying on manufacturer-led testing and limited evaluation across movement modes and environments, including swimming.[3]

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Traditional HR monitors (THR) utilize chest straps embedded with electrocardio sensors, worn against the skin below the sternum.[4,5] These sensors transmit data via telemetry or Bluetooth to an external device (i.e. digital watch or electronic mobile device) that stores and displays the HR.[2,3] THR monitors report a high level of agreement with electrocardiogram (ECG) readings[6] but can be impractical during training due to limited data storage capacity, potential skin irritation with prolonged use, and the required use of water or conducting gel (placed between the sensors and skin) to ensure optimal signal strength. Additionally, THR are often worn underneath clothing, which can potentially cause discomfort and reduced signal strength.[4,7]

Swimming is inherently different than other sports: it relies on large range of motion movements of the arms and upper body for propulsion to a greater extent than other sports, the activities are completed with the body in a horizontal orientation, and the body must overcome considerable drag forces for forward movement. In addition, thermal stress is more pronounced in the water than in equivalent air temperatures.[8] The skill of the swimmer and the swimming stroke can also alter the economy of movement.[9] Therefore, the measurement of HR during swimming provides unique challenges not seen in other sports. Coaches often rely on HR as a tool for prescribing and monitoring the training intensity of their athletes.[10] Both Polar (Polar Electro, Kempele, Finland). and Garmin (Garmin LTD, Olathe, KS, USA) sell traditional chest straps that are marketed for use during swimming. However, the practicality of using these chest straps for swimmers can be limited due to difficulty in maintaining the strap's position on the torso while swimming.[11] This is especially pronounced among male swimmers who do not have the added support of a full body swimsuit to keep the THR strap secured in place. Furthermore, the elasticity of the chest strap degrades over time, leading to movement and displacement of the sensors and consequent incomplete or inaccurate HR measurement.[12]

Photoplethysmography (PPG) is a widely used optical HR technology in contemporary consumer devices that has the potential to address some of the challenges encountered in accurately monitoring HR during physical activity. This technology employs light emitting-diode (LED) lights to transmit various wavelengths of light through the skin and surrounding tissue. The HR is then estimated based on the amount of light reflected back via blood flow.[2] The Polar OH1, a six-LED optical HR sensor, can be securely worn around the bicep, forearm, or temple.[2,13] It has been validated against a traditional chest strap during various activities including running (152.1 vs 151.8 bpm), cycling (132.2 vs 132.5 bpm), soccer (132.6 vs 132.5 bpm), walking (80.6 vs 80.4 bpm), kayaking (121.5 vs 120.6 bpm), and tennis (152.3 vs 151.3 bpm), when worn on the forearm, upper arm, or temple.[13] Moreover, the OH1's validity was demonstrated when positioned on the temple, beneath a cap, and fastened with a headband during activities involving moderate to high physical exertion, such as walking on a treadmill or using a stationary bike (ICC = 0.99).[4]

PPG-based sensor accuracy requires a strong and continuous PPG–skin contact and pressure.[14,15] Unlike THR straps, water reduces the signal accuracy by interrupting contact between the PPG sensor and the skin. Previous research has emphasized the influence of movement artifacts on the accuracy of OHR often arising from factors like PPG sensor displacement against the skin, alterations in blood flow dynamics (vasoconstriction and dilation), and changes in ambient temperature.[14] These issues are especially relevant for swimmers who use their arms across all swimming strokes. Such reliance on arm movements is likely to compromise the accuracy of devices worn on the wrist or arm, leading to a reduction in data quality. Moreover, swimmers also contend with varying water temperatures, which can directly influence the device's accuracy.[14]

Because HR is useful for tracking exercise intensity, it is important to validate the use of optical HR monitors during swimming. Therefore, the purpose of this study was to examine the convergent validity of two HR monitors. Specifically, an OHR (Polar OH1) worn against an individual's temple to monitor HR when compared to a THR (Polar H10) across intensities. Additionally, we aimed to assess differences in HR by monitors during different swimming strokes and determine the overall feasibility of using an optical monitor during swimming. Our hypothesis was that the OHR would provide similar measuring capabilities as the THR.

Methods

Participants

Twenty participants (8M, 12F) were recruited from a division III swimming team via word-of-mouth and email. One male subject was excluded from the analysis due to equipment malfunction during testing and failing to record data. The total sample size was determined based on previous studies with similar designs [4,11] but was ultimately constrained by the "pragmatics of recruitment and the necessities for examining feasibility" as noted by Leon et al[16] which are fundamental to pilot studies. The inclusion criteria included: current members of the Hope College Swim Team and had previously been medically cleared for intercollegiate athletics participation via a preseason athlete physical. Participants were excluded if they had any swimming restrictions or limitations due to injury at the time of the study. Prior to completing any study procedures, all participants completed an Institutional Review Board (IRB) approved informed consent. The study protocol (IRB# 1238) was approved by the college's IRB, adhered to the ethical standards of the Helsinki Declaration and was carried out fully in accordance with the ethical standards of the *International Journal of Exercise Science*.[17]

Protocol

To assess the accuracy of the OHR during swimming, participants wore two devices. The THR was secured around the subject's chest and paired with the Polar V800 watch (worn on the subject's wrist). The OHR was placed against the subject's temple (Figure 1), secured to the subject's goggle straps, and secured under the swim cap). Participants completed approximately 20 minutes of swimming including freestyle at three different intensities and two different intensities of their "preferred" stroke. The two swim protocols were separated by a period of passive recovery with HR continually recorded on both devices.

Participants reported for one testing session. Upon arrival, body mass was measured to the nearest 0.1kg using a standard scale (Detecto, Webb City, MO, USA). Participants self-reported their height which was recorded in centimeters (Table 1). Participants were members of a Division III National Collegiate Athletic Association (NCAA) swimming team. They had completed their season one week prior to the start of data collection. Thus, training volume was low, given that participants had completed a taper week, followed by conference championship, and subsequent week off of training (first week of their offseason). Participants were primarily underclassmen (freshman and sophomores).

Table 1. Subject Demographics

	Male	Female	Total
Participants (n)	7	12	19
Height (cm)	178.0 ± 4.13	170.6 ± 6.84	173.3 ± 6.90
Weight (kg)	75.4 ± 7.20	67.5 ± 9.90	70.4 ± 9.63

Research assistants outfitted the participants with the THR. The THR was placed directly against the skin around the sternum at the level of the xiphoid process. Ultrasound gel was spread across the chest strap to assist in accurate HR readings. A Polar V800 watch, paired to the THR, was fastened to subject's preferred wrist. Then, the OHR was attached to the subject's goggle strap on their preferred side and secured under the edge of their cap (Figure 1). The OHR was placed directly against the skin and care was taken ensure that hair was not between the OHR and the skin as it could disrupt the PPG signal. The swimmers then completed a swim protocol in a 25m pool similar to a set included in a standard swim-training practice session. There were two swimming protocols that each subject took part in: freestyle and "preferred" stroke. Each swimmer proceeded through the freestyle protocol once followed by one round of the preferred stroke protocol.

a b

Figure 1. Placement of the OH1: a) against the temple b) under a swim cap

Freestyle Protocol.

Participants performed a series of nine 75m freestyle swims with the goal of increasing their HR and effort throughout the series. The first four 75m swims were "light" intensity (HR 145-155 bpm). The next three 75m swims were at "moderate" intensity (HR 155-170bpm). The final two 75m swims, participants were instructed to swim at a "vigorous" intensity (HR > 170bpm). HR from the Polar V800 watch was verbally reported by the subject and recorded by investigators after each 75m. The participants were given approximately 15 seconds rest between each 75m before beginning the next 75m bout. These intensities were chosen as they were the intensity categories utilized by the team's coaches during their swimming practices. The participants in this study were comfortable with monitoring their intensity efforts based on these HR ranges. Thus, familiarity with these intensity categories by all of the participants was the primary reason for their application in this study. Additionally, we aimed to determine device accuracy across a range of exercise intensities, as previous work has found OHR technology can struggle when transitioning between intensities.[5]

Recovery.

Participants held onto the side of the pool and rested in the pool for two minutes following the completion of the freestyle protocol.[18] HR was reported from the Polar V800 at the half-way mark of their rest interval and immediately before they began the "preferred" stroke protocol.

Preferred Stroke Protocol.

Each subject was instructed to swim with their preferred stroke (i.e., freestyle, backstroke, breaststroke, or butterfly) for this protocol. Participants performed a 100m swim of said stroke at a "moderate" pace. This was described to the participants as a pace they would use during a "warm up" prior to a meet. HR was recorded immediately upon completing this distance. Following completion of the 100m, participants rested for one minute and then performed a second 100m swim at high intensity or "race-pace". HR was recorded one final time upon completion of this swim. This better reflects typical training and competition conditions. Swimming strokes differ in mechanics, body orientation, and breathing patterns, which may influence cardiovascular responses and the accuracy of physiological measurements such as heart rate. Previous research[19] has shown that physiological responses during swimming can vary across strokes.

HR from the THR was recorded manually at the end of each lap and cross-checked with the time stamped data recorded by the Polar V800. Following the end of the preferred stroke protocol, data from each device were downloaded into a Comma Separated Value (CSV) file. Pool temperature was recorded in degrees Celsius (ºC), at the start of each session using a digital thermometer (ThermoWorks, Utah). The pool temperature was 26 ºC for the duration of the study (± 0.1 degree).

Data were collected between 5-8am and 3-6pm over a 9-day period. Trained student-researchers collected all data while supervised by the principal investigator.

Statistical Analysis

It should be noted that post hoc power analysis to detect difference by stroke indicated that this study was under-powered for this analysis (power > 0.10). Our analysis indicated that the achieved power was 0.41, while an estimated 47 participants would have been needed to reach a power of 0.80. Our sample size was limited by the number of available swim team members at the end of their competitive season and further restricted by the COVID-19 shutdown, which prevented additional recruitment. All data were reported as means and standard deviations. Paired t-tests were performed to compare the percent of HR data collected across all intensities by the OHR and THR. Then, mean HR values were calculated for each monitor during each exercise intensity. Missing HR values were skipped without replacement in the calculation of the mean HR values. To determine if statistical differences occurred between HR data, repeated measures ANOVAs (RM ANOVA) were completed between the mean HR values collected by the OHR and THR during each condition. Mauchly's test of sphericity was verified before interpretation of the results. When appropriate, post hoc analyses were completed using pairwise comparisons with Bonferroni adjustment to determine any significant differences. The Bonferroni adjustment was used to reduce the chances of committing a type I error. Given the six different conditions (three intensities of the freestyle protocol, one recovery interval, and two intensities of their preferred stroke), the adjusted p-value was 0.05/6 or $\alpha = 0.0083$. To determine statistical equivalence, a two one-sided t-test (TOST) was determined for each exercise intensity. For this analysis, 95% confidence intervals (CI) were constructed around the mean differences between monitors for each exercise intensity. If the confidence intervals fell entirely within the 5% equivalence bounds, then the data were considered equivalent ($p < 0.05$). Statistical analyses were performed using SPSS software (Version 28, SPSS Inc, Chicago IL, USA) and Microsoft Excel (Version 2108, Microsoft Corp. Redmond, WA, USA). Statistical significance was set at an alpha level of 0.05.

Results

Data from 19 participants (7M, 12F) were included in the data analysis (see Table 1). Because there were no statistical differences by the sex of the participants in the overall mean HR difference by monitor ($p = 0.44$), all data were analyzed as one group.

Each monitor was programmed to record HR in one second epochs. The resulting data were then exported into a CSV file, where any missing data were indicated by an empty cell. The OHR recorded significantly more data during the trials with an average of 99.9 ± 0.1% of the data, while the THR recorded 58.9 ± 31.3% of the data ($p < 0.001$) (Figure 2).

HR differences by monitor varied from 3.8±5.4 bpm (recovery periods) to 6.2±9.8 bpm (vigorous intensity freestyle). RM ANOVA demonstrated a significant difference between HR measurements by monitor ($p = 0.019$). There was also a significant monitor × intensity interaction effect ($p = 0.009$). Post hoc analysis indicated significant differences between methods during recovery ($p = 0.007$) and during freestyle at vigorous intensity ($p = 0.013$). Figure 3 presents the mean HR values for each monitor and each exercise intensity.
HR differences varied more during the participant's preferred stroke with HR differences of 10.8±1.2 bpm (moderate intensity) to 9.9 ± 5.7 bpm (vigorous intensity). RM ANOVA demonstrated a significant difference between HR measurements by monitor ($p = 0.003$). However, there was no statistically significant monitor × intensity interaction effect ($p = 0.906$) (Figure 4).

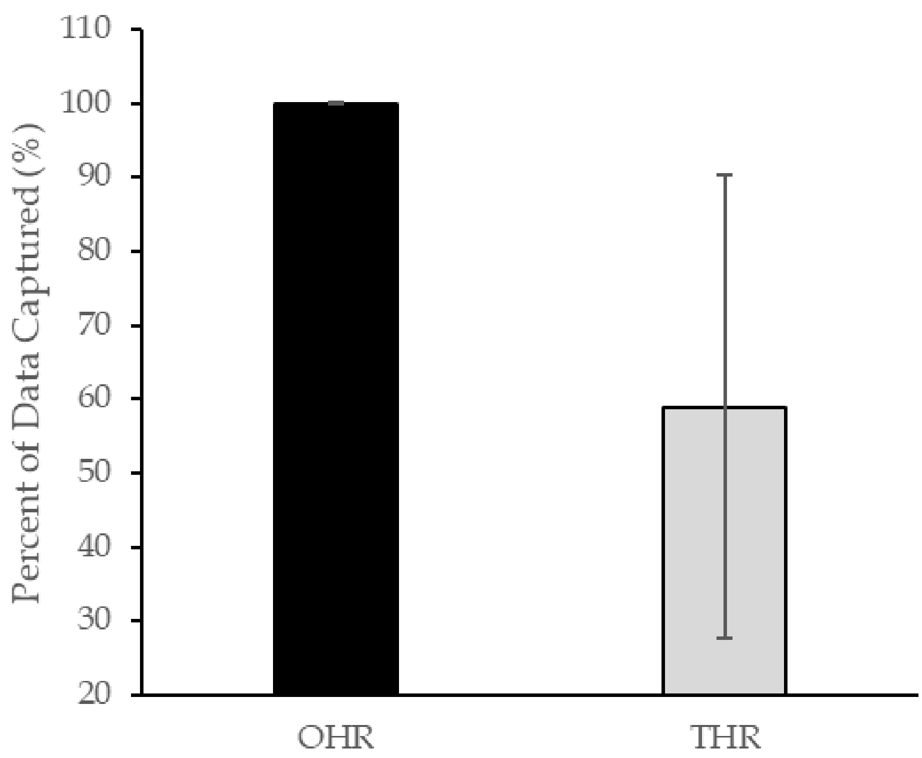

Figure 2. Percent of data captured by each device. * Significant difference between devices ($p<0.001$)

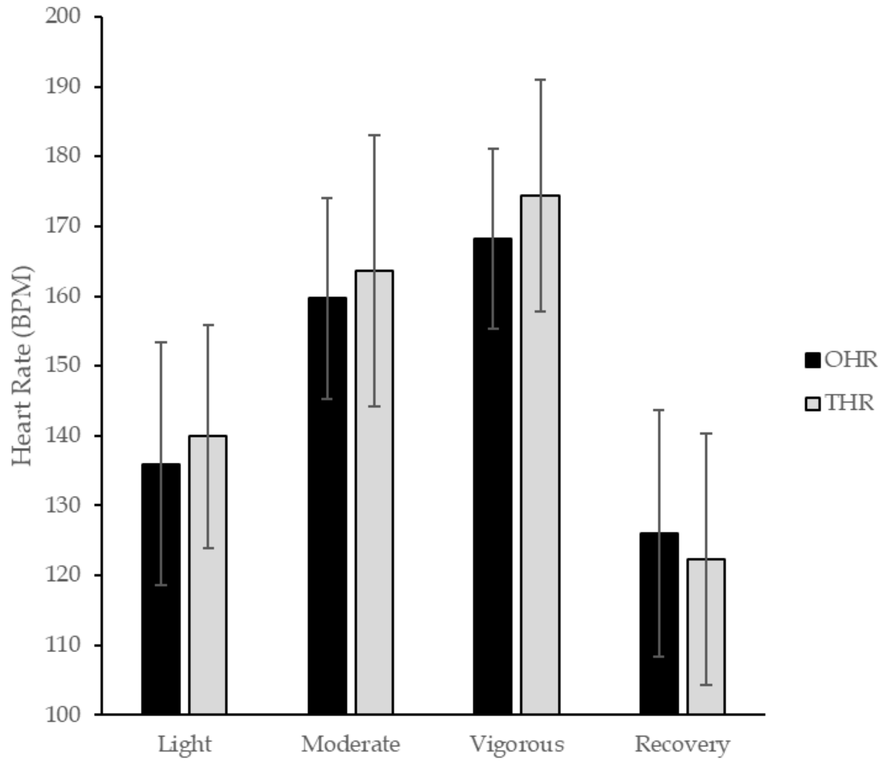

Figure 3. Difference in mean HR between the two devices at light, moderate, vigorous swimming intensities and recovery. * Significant difference between devices ($p<0.05$)

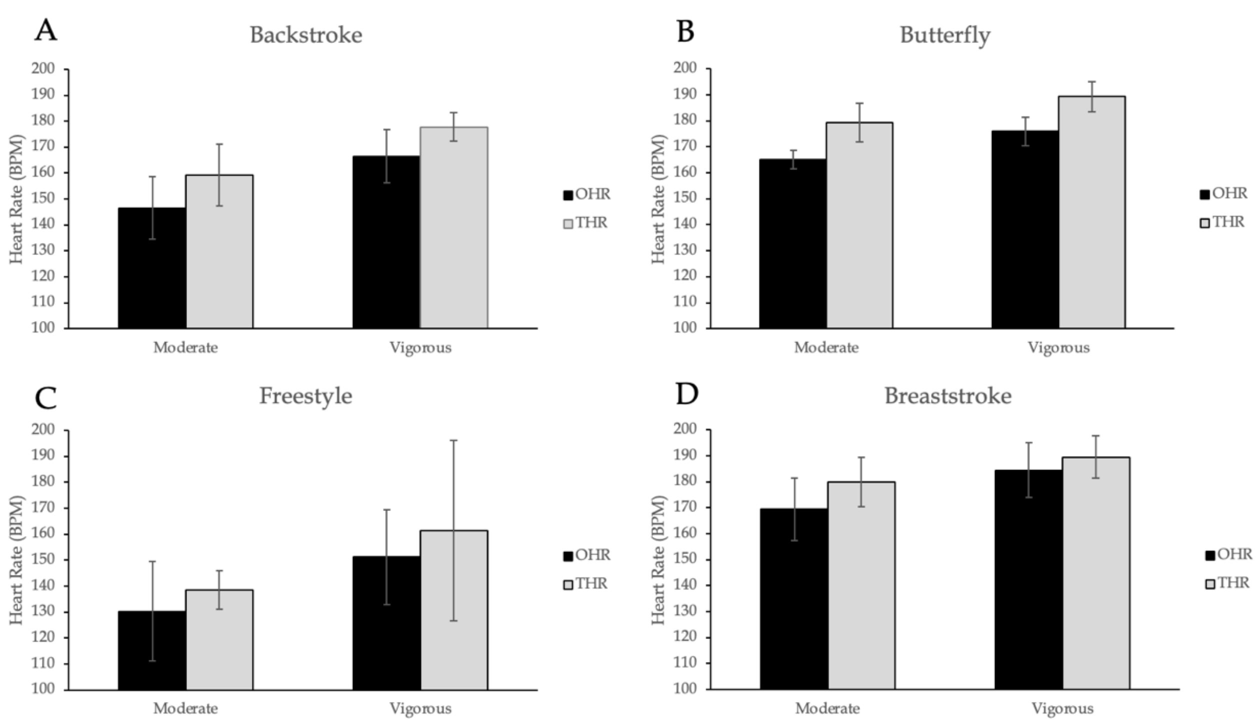

Figure 4. Difference in mean HR between devices during different swim strokes and intensities.

The overall calculated 95% CI equivalence range based on the mean difference in HR by method was -11.7 to 1.4 bpm. The actual 95% CI was -2.3 to 2.3 bpm. As this range did not completely fall within the calculated 95% equivalence range, the HR values from the two monitors were not considered statistically equivalent ($p > 0.05$). Further equivalence analyses found that HR values from the two monitors were statistically equivalent at rest and during low and moderate intensity freestyle swims ($p < 0.05$). However, statistical equivalence did not occur during vigorous intensity freestyle swims or during moderate or vigorous intensity swims using the participant's preferred stroke ($p > 0.05$).

Discussion

The purpose of this study was to compare the convergent validity of the Polar OH1 monitor (OHR) when worn at the temple to a traditional H10 chest strap (THR) during swimming of varying intensities and strokes. Our findings suggest that while the OHR is a capable device for *capturing* continuous (second-by-second) HR data during swimming, it significantly underestimates HR compared to a THR.

Although the OHR underestimated heart rate in some conditions, the equivalence analyses indicate that this underestimation was not uniform across all intensities or strokes. Heart rate values were statistically equivalent between devices at rest and during low- and moderate-intensity freestyle swimming, suggesting that the OHR device may provide sufficiently accurate HR estimates in these conditions. In contrast, equivalence was not observed during vigorous-intensity freestyle swimming or during moderate- and vigorous-intensity swimming when using the participant's preferred stroke. This suggests that increases in intensity and changes in stroke mechanics may increase measurement error, limiting the utility of OHR devices under more physiologically demanding swimming conditions. These equivalence results provide a more nuanced interpretation of device performance than mean differences alone and may be more informative for coaches/athletes considering the use of OHR devices when swimming.

Few studies have used an optical HR monitor during swimming[7,20,21] or other water-based activities.[22] To date, there has been one study that examined the validity of the Polar OH1 worn at the temple in monitoring HR during front crawl (i.e. freestyle) swimming.[11] Olstad and Zinner compared two PPG-devices (Polar OH1 on the temple and Polar M600 on the wrist) to a traditional chest strap (H10) during a swimming activity.[11] The OH1 worn at the temple was found to be more valid in swimming than the M600 wrist worn monitor for three possible reasons: lower amounts of head movement compared to movements of the arm and wrist in swimming, less fluid film between the OH1 and temple, and a stronger pulse pressure at the temple allowing for increased recognition.[11]

The movement of the THR chest strap during swimming was a significant challenge for the assessment of HR in the present study. The frequent adjustments to the strap lead to interruptions in HR signal and resulted in only 58.98 ± 31.3% of the participants' HR data being captured by the device (Figure 2). A recent study examined the Polar Verity Sense (the updated version of the OH1) when worn on both the temple and the arm during different intensity swim strokes.[23] The authors reported near perfect agreement between the OHR worn on the temple and the gold standard THR. However, the authors reported using kinesiology tape to cover and secure the chest strap (via email communication with study authors).[23]

As noted in a previous study,[11] strap movement is a common issue for male swimmers, who do not have the advantage of a swimming suits to aid in securing the strap during swimming.

As such, a major source of error can occur: The device loses contact with the skin leading to water exposure against the LED that can then disturb the electrical signals, re-routing the signal, ultimately preventing detection of the cardiac activity through the sensors. Previously, investigators have sought to address this issue by having their male participants wear full body swimsuits that cover the thoracic region[11] or securing the strap with tape.[23] However, this solution is suboptimal in our population for two reasons. One, there is a potential for a restrictive full body swimsuit to cause discomfort and negatively impact performance. Two, and most importantly, the Fédération international de natation (FINA), regulations state that competition suits for males cannot extend above the navel or below the knee. This renders it impractical to train in attire that differs from what the athlete is allowed to wear during competition [24]. Additionally, participants in the current study reported that the chest strap felt uncomfortable during the swim, a finding that also mirrors previous research.[11,25]

The OHR presented fewer challenges compared to the THR. First, it was anchored to the subject's goggles and secured against the skin under the subject's swim cap. As a result, it captured 99.9 ± 0.1% of the participants' HR data (Figure 2). However, it should be noted that this placement restricted the participants from lifting and clearing their goggles during the session without risking displacing the sensor and encountering the same previously mentioned errors to which the chest strap is prone. Second, linking to a mobile device only allowed for review of the data after practice and not in real time due to Bluetooth issues transmitting underwater. This is a limitation for athletes/coaches who would prefer to are monitor their HR in real time rather than after the training session.

Historically, swim coaches have relied on metrics such as external load and speed to guide athlete training.[26] Other studies have attempted to measure internal load in swimming using oxygen consumption.[27] However, respiratory measurements require specialized equipment to capture during swimming that could alter swimming mechanics and are not practical for training sessions. Therefore, HR remains the optimal physiological variable to utilize during swim training, further increasing the necessity to validate PPG devices employed by coaches and athletes.[22,26,28]

Training at the appropriate intensity is imperative for athletes to improve performance and to reduce the risk of overtraining syndrome[1,11] thus consistent HR monitoring can allow coaches to regulate training intensity.[1] Furthermore, elite swimming programs are beginning to incorporate other modes of exercise into their workout routines to increase cardiovascular fitness while avoiding overstressing the muscles used in swimming.[7] Valid HR monitors for swimming are essential for coaches to design programs tailored to different types of swimmers such as sprinters, middle distance, and distance swimmers who each benefit from training at different intensities.[7] Self-estimation of max HR by swimmers[7] or using a prediction model to calculate HRmax in swimming has been suggested,[20] but focusing on HR zones, rather than a specific number, to monitor intensity is optimal. As swimming training programs also often incorporate other training modes in addition to their training in the pool and HR varies between these various forms of exercise, it is increasingly important to be able to accurately monitor HR both in and out of the pool in order to regulate intensity.

Our study did have limitations. First, there was very little variability of the water temperature during data collection. Future research should investigate the role of the underwater environment and variable water temperatures on the accuracy of OHR monitors.[29] Secondly, it should be noted that our study did include only participants that were of European descent. Previous research has indicated that OHR measurements are less accurate in participants with darker skin tones compared to those with lighter skin tones.[14] Future research should examine device accuracy across a mor ethnically diverse population. Lastly, a study design with both dry land and water testing protocols would enable direct comparison to determine the effects of water and temperature on device accuracy during exercise.

Aerobic training relies on HR as an important physiological variable to establish workout intensity. Employing a sensor on the temple has the potential to negate these challenges due to minimal movement artifact and reduced water interference when the device is secured to the goggles and worn under the swim cap. Thus, an optical device worn on the temple offers a potential solution for coaches and swimmers who use HR data to guide their training. And, while our data indicate the OH1 captures HR more consistently than a traditional chest strap (99.9 vs. 58.98 %) it reports lower HR values compared to the criterion measure. Establishing convergent validity is a crucial first step in determining whether these devices provide comparable measurements under similar conditions. The findings from this study will help guide future, larger-scale research on their practical applications. Therefore, based on our findings, we feel this technology shows promise for HR collection during swimming, but caution that due to both the above stated limitations and limited number of participants, further research is needed to confirm device accuracy.

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