FORM®
SMART SWIM GOGGLES

Executive Summary

Motivation

- Heart rate training is becoming increasingly popular for endurance athletes to optimize their fitness and performance.
- Effective heart rate training requires both accurate and consistent measurement of real-time heart rate. The gold standard for both is an ECG-based chest-worn HR strap. However, ECG straps have no ability on their own to deliver data in real-time to an athlete. Instead, all data is reviewed post-swim on a mobile device or desktop platform.
- The FORM Smart Swim 2 goggles feature an integrated optical heart rate sensor to provide continuous heart rate feedback to the swimmer.
- The FORM Smart Swim 2 goggles offer a heads-up display which enables the athlete to see real-time heart rate. Real-time data and insights can further elevate the effectiveness of swim training.

Objective

- Find out the accuracy of the FORM Smart Swim 2 goggles heart rate during swimming, by comparing it to the gold standard heart rate chest strap used by athletes.
- Find out how FORM Smart Swim 2 goggles' heart rate accuracy compares to wrist-based heart rate devices that are routinely worn by endurance athletes.

Key Findings

- The FORM Smart Swim 2 goggles demonstrate an overall accuracy rate of 97% in monitoring an individual's true heart rate compared to an ECG chest strap.
- The FORM Smart Swim 2 goggles exhibit an average deviation of +/- 4 beats per minute (bpm) in heart rate measurement compared to an ECG chest strap. In contrast, wrist-based heart rate monitoring displays a variance of +/-10 bpm compared to an ECG chest strap.

Conclusion

- Our findings clearly show that the integrated optical heart rate sensor on the FORM Smart Swim 2 goggles provides a more accurate and consistent measurement of real-time heart rate vs a wrist-based HR sensor. Additionally, the heads-up display found in the FORM goggles makes HR data more accessible and actionable than any other HR technology on the market for the triathlon and swim communities. This positions the FORM Smart Swim 2 as an ideal training tool for triathletes, coaches, and swimmers interested in heart rate-based training.

FORM
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White Paper

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Introduction

Swimmers can improve their performance by adjusting their workout intensity and frequency. Adding in heart rate information can allow the swimmer to adjust workout loads to prevent overtraining and injuries [1]. During exercise, having continuous access to heart rate feedback has been shown to improve cardiovascular health [2].

The current commercial gold standard for measuring heart rate during exercise is single-lead electrocardiography (ECG) chest straps [3]. Although chest straps are easily available, during swimming chest straps are uncomfortable, difficult to wear and often slip off. Without a wetsuit to hold the chest strap in place, chest strap data can be very inaccurate [4]. Optical devices that acquire a Photoplethysmography (PPG) signal at the wrist and the temple have been validated against heart rate chest straps to be an acceptable alternative [5].

Several studies have compared wristwatch heart rate monitors to chest straps and highlighted the difficulty of acquiring heart rate in the water. Two studies by Budig et al. looked at the accuracy of a wrist-worn optical sensor [4], [6]. The first study in 2019 only compared heart rate signals during running and cycling between a Garmin Vivoactive HR and a Garmin chest strap [4]. The study skipped validating heart rate during swimming, even though swimming data was used in the study to compare differences in distance measurement [4]. The second study in 2022 compared a Garmin Forerunner 945 with a chest strap during swimming [6]. The Mean Absolute Percent error increased from 2.85%, without the swim data, to 7.18% with the swim data [6]. This means that the accuracy of wristwatch heart rate degraded by 4.33% when the researchers added swimming data to the calculation, further illustrating the difficulty of getting an accurate heart rate during swimming. Additionally, swimmers with only wrist heart rate monitors will be able to read the displayed heart rate exclusively during rest, and will not be able to adjust their effort mid-length.

FORM Smart Swim Goggles have an augmented reality screen that allows the swimmer to see accurate real-time metrics like stroke rate, length count, pace and stroke type [7]. The new FORM Smart Swim 2 goggles include all the existing swimming metrics, however, the biggest differentiating feature is an integrated heart rate sensor. By having an onboard heart rate sensor, swimmers can get real-time feedback on their heart rate, including heart rate zones while they are swimming. The objective of this paper is to validate the heart rate accuracy against a commercial (gold standard ECG) chest strap and a wrist-based heart rate monitor.

Technology Background

FORM's Smart Swim 2 goggles utilize optical sensors to acquire heart rate data using PPG. PPG signals are acquired by placing an optical sensor on the surface of the skin, and measuring the amount of light reflected back to the sensor. The amount of light is proportional to the change in oxygenated and deoxygenated blood in the body [8]. During a swim, users can see their heart rate and/or heart rate zones continuously in the augmented reality display. The heart rate zone training can be incorporated into the Workouts features of the FORM goggles.

Study 1: Validating FORM Smart Swim 2 Goggles

Thirty-one participants wore the FORM Smart Swim 2 goggles and a chest strap during their swim. Each participant swam a prescribed 500m workout that was loaded onto the FORM Smart Swim 2 goggles. The workout varied in interval lengths and intensities. Depending on the participants' swimming experience some swam backstroke and breaststroke in addition to freestyle. To prevent the chest strap from sliding or coming off during the swim, women wore a one-piece swimsuit, and the chest strap was knotted in place so the fastener would not slide around for men. The FORM Smart Swim 2 goggles were worn under the swim cap, and it was ensured that hair was not interfering with the goggles' heart rate sensor. The FORM Smart Swim 2 goggles straps were at a comfortable tightness that prevented the goggles from moving too much during the swim.

Results

After the swim, the heart rate data from the chest strap was aligned with the heart rate from the FORM Smart Swim 2 goggles using epoch timestamps. Figure 1 is an example of the heart rate signals from both devices during one participant's swim. A Bland Altman plot (see Figure 2) was used to evaluate the bias between the heart rate signals for both devices. The Mean Absolute Error (MAE) and Mean Absolute Percent error (MAPE) across all participants were ±3.0 beats per minute (BPM) and 3%, respectively. This means the FORM Smart Swim 2 has an accuracy of 97%. To investigate the levels of agreement, the correlation coefficient was found using Lin's Concordance Correlation. If the heart rate from the FORM Smart Swim 2 does not match the chest strap the Lin's Concordance Correlation would be 0, while a perfect match gives an agreement of 1. For this dataset the coefficient was 0.95, indicating a high level of agreement. In Figure 3 a scatter plot of the chest strap and the FORM Smart Swim 2 illustrates the high level of agreement.

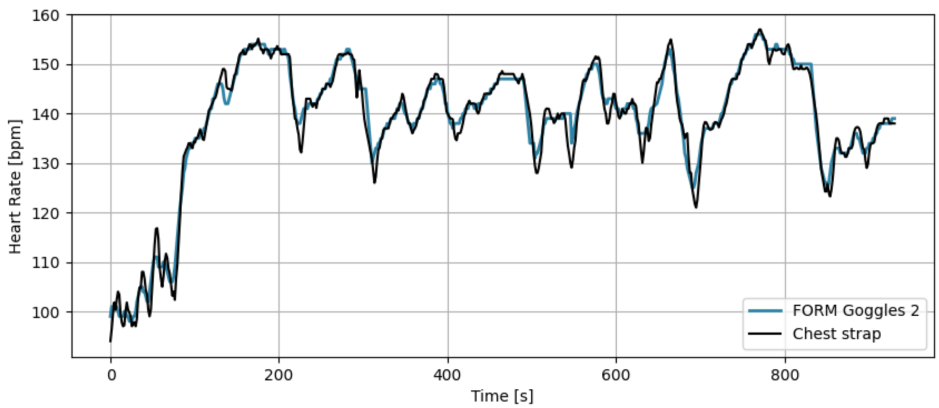

Figure 1: The participant's heart rate signal from the FORM Smart Swims 2 goggles and the chest strap are shown. Both signals have similar waveforms and the MAE for this swim was ±1.3 BPM.

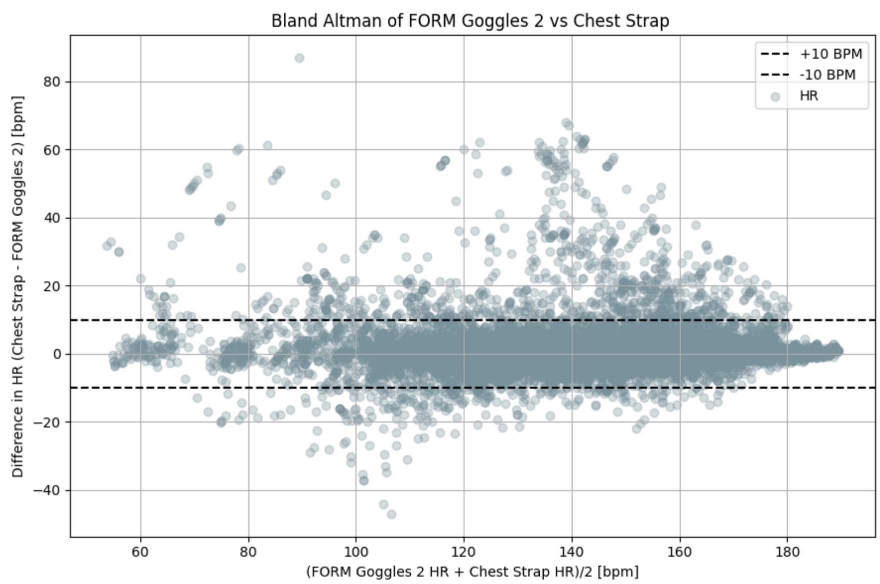

Figure 2: A Bland-Altman plot (n=17831) showing the bias between the mean heart rate and the difference between the FORM Smart Swim 2 goggles and the chest strap. The MAE across all participants was ±1.3 BPM, and the MAPE across all participants was 3.0 %, with 93% of the data residing within ± 10 BPM.

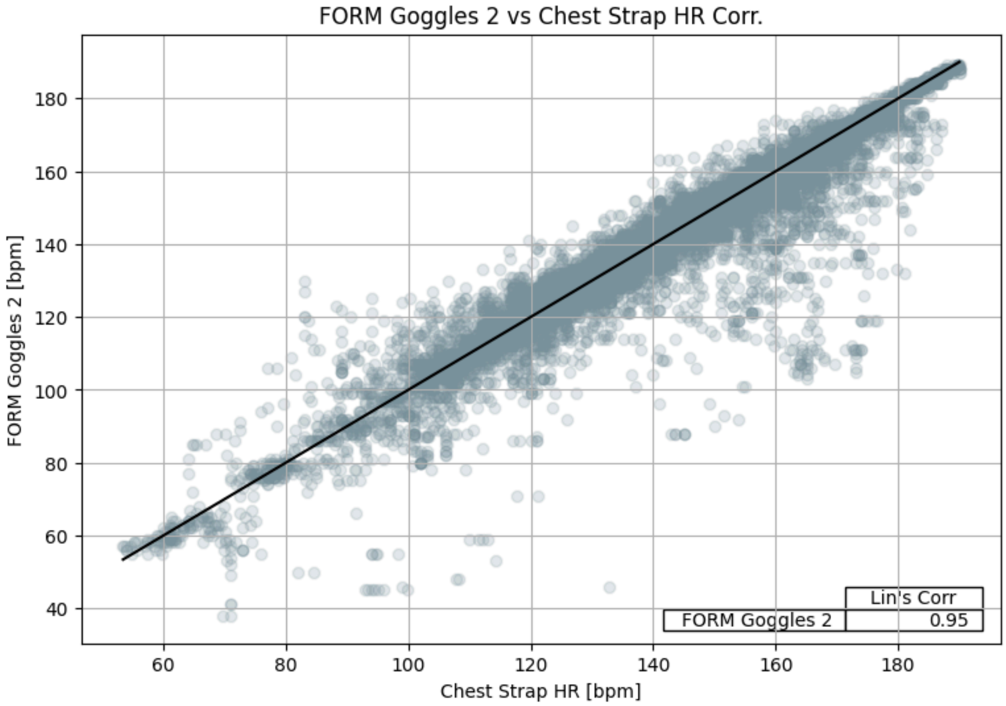

Figure 3: A scatter plot comparing the Chest strap heart rate data to the FORM Smart Swim 2 goggles heart rate data. Lin's Concordance Correlation between both datasets was 0.95, indicating a high level of agreement.

Study 2: Comparing FORM Smart Swim 2 Goggles to Wrist-Based HR

Twelve out of the 31 participants in Study 1 also wore a leading swimming watch with a built-in optical heart sensor on their chosen wrist. The twelve participants had equal male and female representation and ranged in age from 20 to 40 years old.

Results

After the swim, the heart rate from the chest strap and watch was aligned with the heart rate from the FORM Smart Swim 2 goggles using epoch time. Figure 4 is an example of the heart rate signals from all three devices during one participant's swim. On an aggregate level across the 12 participants, the FORM Smart Swim 2 goggles were 4% or 6.4 beats per minute more accurate than the swimming watch with a built-in optical heart sensor. When the difference in MAE was assessed on a beat-by-beat basis, it was found that 80% of FORM's Smart Swim 2 data is within 5 BPM accuracy of the chest strap, while the swimming watch with a built-in optical heart sensor has 50% of its data within 5 BPM. Figure 5 shows the percent of data less than a given error rate.

The scatter plot shown in Figure 6 illustrates the correlation between the devices. FORM Smart Swims 2 goggles have an excellent level of agreement with the ECG chest strap, with the Lin's Concordance Correlation equal to 0.94, while the swimming watch with a built-in optical heart sensor's Lin's Concordance Correlation equals 0.73, indicating a good level of agreement.

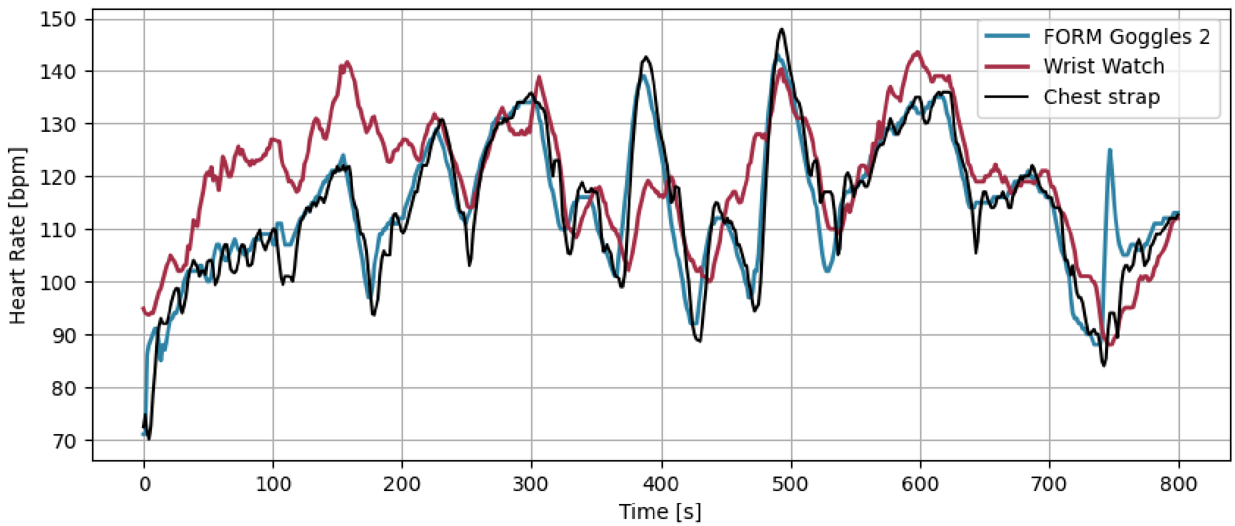

Figure 4: The aligned heart rate signals from a single participant's swim. The MAE between the FORM Smart Swim 2 goggles and the chest strap for this swim was ±3.6 BPM, while the MAE between the swimming watch with a built-in optical heart sensor and the chest strap was ±9.0 BPM.

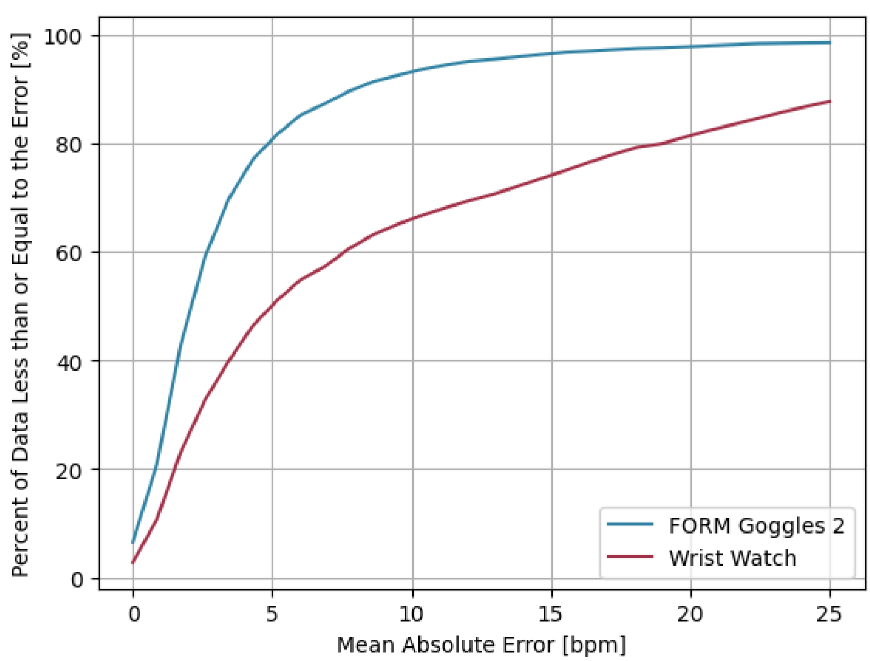

Figure 5: The percentage of heart rate within a given error, compared to the chest strap. The FORM Smart Swims 2 goggles have 80.9% of the data within 5 BPM, while the swimming watch with a built-in optical heart sensor has 50.5% within 5 BPM.

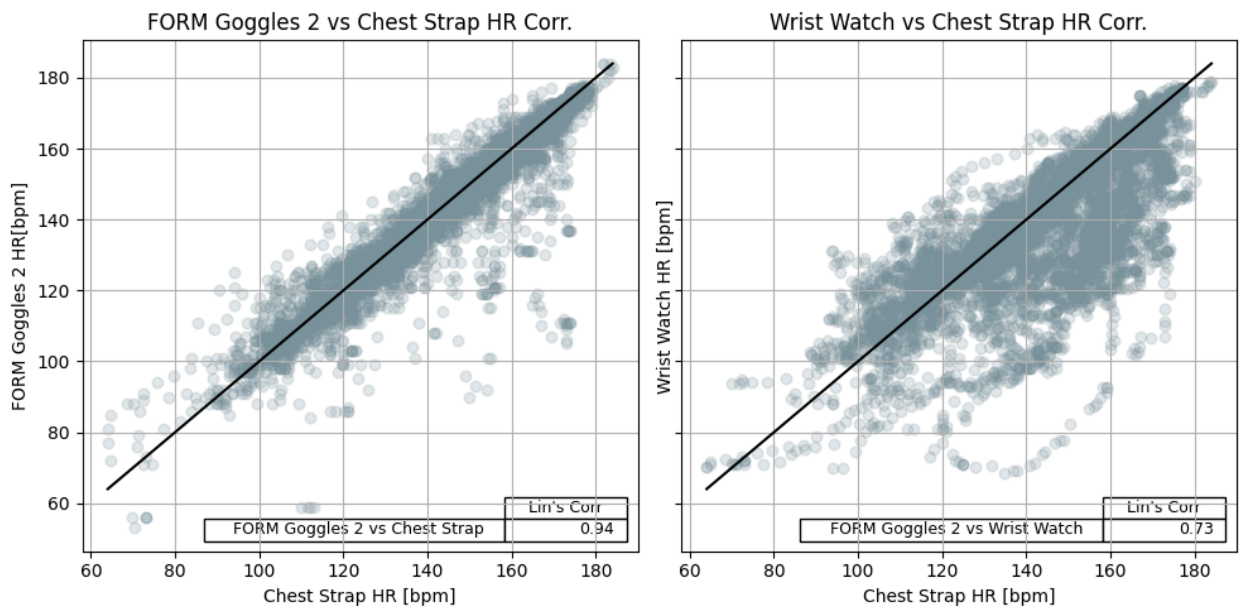

Figure 6: (left) A scatter plot comparing the Chest strap heart rate data to the FORM Smart Swim 2 goggles heart rate data. Lin's Concordance Correlation between both datasets was 0.94, indicating a high level of agreement. (right) A scatter plot comparing the Chest strap heart rate data to the leading swimming watch's heart rate data. Lin's Concordance Correlation between both datasets was 0.73, indicating a lower level of agreement.

Discussion

In this White Paper, FORM conducted two studies. Study 1 examined the validity of HR measured by the FORM Smart Swim 2 goggles, compared to a gold standard ECG chest strap. Study 2 then compared the accuracy of FORM Smart Swim 2 to a swimming watch with a built-in optical heart sensor, which is a popular and common mode of HR assessment by swimmers and triathletes.

FORM's Smart Swim 2 goggles were found to be a highly valid measure of heart rate, with a 97% degree of accuracy when compared to heart rate from an ECG chest strap. When comparing FORM's Smart Swim 2 goggles to the widely used swimming watch with a built-in optical heart sensor that captures wrist-based HR, FORM's Smart Swim 2 goggles had a higher level of agreement using Lin's Concordance Correlation, with the chest strap (0.94 vs. 0.73), as well as being 4% more accurate than the leading swimming watch across all 12 participants. A

4% difference in accuracy equates to ~7 BPM, which can incorrectly place an individual swimming to specific heart rate zones into the adjacent zone.

The results from Studies 1 and 2 are aligned with previous studies which show that the temple is a great place to acquire PPG-based heart rate. For example, a study comparing the Polar OH1 and a Polar M600 to a Polar chest strap during swimming found the level of agreement between Polar OH1 and the chest strap was higher than the wrist-based M600 and the chest strap. Olstad & Zinner noted in their study that wrist-based devices are more susceptible to interference by water and movement artifacts, compared to devices acquiring heart rate at the temple [5]. As such, FORM's Smart Swim 2 goggles' ability to acquire PPG from the temple allows for a heart rate signal to be derived that is comparable to ECG-based heart rate, as well as demonstrating superior accuracy compared to commercial wrist-based heart rate devices, Table 1 summarizes those key results.

Table 1: Summary of results comparing FORM Smart Swim 2 goggles to a chest strap, and a wrist-worn heart rate monitor to a chest strap.

	Accuracy (in %)	MAE (in BPM)	Percent of data within 5 BPM	Lin's Concordance Correlation
FORM Smart Swim 2 compared to a chest strap	97%	±3.7 BPM	80.9%	0.94
Wrist-worn heart rate compared to a chest strap	93%	±10.1 BPM	50.5%	0.73

Conclusion

The FORM Smart Swim 2 goggles can be used as a highly accurate heart rate device. Compared to the commonly used wristwatch heart rate monitor, the FORM Smart Swim 2 is more accurate by ~7 BPM. Moreover, the augmented reality display unique to FORM's goggles provides swimmers with real-time heart rates that they can monitor continuously. Workouts that are designed using FORM's Workout Builder can incorporate heart rate zones as another way to accurately infer effort levels when swimming. As such, the FORM Smart Swim 2 goggles are an effective way to add heart rate training into every swimmer's training plan.

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