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RESEARCH ARTICLE
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Feasibility of Physiological Assessments for Long-Distance Swimming Safety in Open Water Using Virtual Reality Settings

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Abstract:

Introduction: Approximately 240,000 people drown annually worldwide. The benefits of programs of long-distance swimming in the sea are important for children. However, due to safety concerns, fewer schools are implementing the programs. A better system for monitoring heart rate that enables the detection of physiological abnormalities and improves the safety of long-distance swimming is needed. In this feasibility study, a system was developed for an open-water setting. Furthermore, we explored acute stress responses using Virtual Reality (VR) as a potential screening tool.

Methods: 40 healthy subjects (28 males, 12 females; age: 18 ± 0.4 years) were timed in the 400m breaststroke, and their peak oxygen uptake (peak VO_2) was measured; heart rate was monitored during long-distance swimming in the sea. Furthermore, cardiac autonomic nerve activity was measured during swimming VR exposure.

Results: A significant correlation was observed between heart rate during long-distance swimming in the sea and the 400m breaststroke time ($r = 0.46$, $p < 0.01$), but not at peak VO_2 ($r = -0.10$, n.s.). A rapid increase in a subject's heart rate was observed immediately before fitting the buoyancy device. Sympathetic activity after VR exposure was significantly higher than before exposure ($p < 0.05$).

Discussion: Heart rate during long-distance swimming depends on swimming ability, not maximum aerobic fitness. Monitoring early heart rate spikes could assist in detecting physiological abnormalities. Furthermore, acute stress responses during VR exposure offer a safe screening method for collecting near-miss data in simulated environments.

Conclusion: Real-time heart rate monitoring showed a relationship between swimming ability and heart rate in the sea. The swimming VR exposure demonstrated potential as an exploratory method for safe risk assessment, though its clinical value requires further validation.

Keywords: Heart rate, Virtual reality, Autonomic nervous system, Long-distance swimming, Feasibility study, Wearable device.

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1. INTRODUCTION

Approximately 240,000 people drown annually worldwide, and drowning is the third leading cause of unintentional accidental deaths [1]. Additionally, drowning is also one of the prime causes of death among children and adolescents [2]. The World Health Organization (WHO) has also recognized drowning as a problem, and in its first-ever report on drowning, the WHO lists "Ten actions to prevent drowning" as causes and counter-measures for water-related accidents [2]. Also, in Europe, the importance of Water Competency, the qualities and abilities necessary for safe activities in and around water, has been demonstrated [3, 4]. In Japan, the benefits of water education, such as long-distance swimming, are important for children [5]. However, due to safety concerns, fewer schools are implementing such programs.

Meta-analysis results on the outcomes of drowning accidents have shown the critical importance of rapid rescue, such as short-term submersion (less than 5 min) and short Emergency Medical Service (EMS) (less than 9 min) [6]. Accordingly, submersion time appears to be the most important predictor in the evaluation of drowning prognosis [6-10]. This emphasizes the importance of prevention and early reaction in the drowning process [11].

During the initial stages of drowning, sudden cold-water immersion and panic often trigger a prominent physiological response known as hyperventilation [12]. This Hyperventilation may cause fluctuations in heart rate and muscle stiffness. As such, measuring and monitoring heart rate could help to detect physiological abnormalities, and potentially improve the safety of water education. Recently, advancements in wearable technology have enabled the continuous remote monitoring of heart rate and Heart Rate Variability (HRV), providing crucial physiological markers for evaluating acute stress and early signs of physical abnormalities [13, 14].

The aim of this feasibility study was to explore physiological responses during distance swimming and simulated environments: 1) to investigate the feasibility of a real-time heart rate monitoring system in an open water setting, and 2) to explore acute stress responses using a Virtual Reality (VR) video as a potential screening tool.

2. MATERIALS AND METHODS

2.1. Study 1: Real-time Heart Rate Monitoring in the Sea

This prospective simulation study was conducted at Kitaura Beach, Japan, under calm sea conditions (wave height < 0.5 m, sea temperature 28.5 °C) [August 2022]. Participants included 40 undergraduate students specializing in health and sports science (age: 18 ± 0.4 years). The inclusion criteria for the participants were healthy undergraduate students specializing in health and sports science who were enrolled in the regular university swimming training course. The exclusion criteria included individuals with a history of cardiovascular abnormalities, respiratory diseases, orthopedic injuries, or any other medical or physical conditions that would preclude safe participation in long-distance open-water swimming. This study was conducted as part of a regular university swimming training course. Rather than using absolute time thresholds, subjects were categorized into five practical training groups based on their 400 m breast-stroke times, while taking into account the overall proportion of students and gender balance in each group (Table **1**). Peak oxygen uptake (VO_2 peak) was measured using a bicycle ergometer at Kawasaki Medical School Hospital four months prior to the sea swim. Heart rate was monitored during a three-hour long-distance swim. To ensure participant safety, a comprehensive safety management protocol was implemented. The rescue fleet consisted of four outboard motorboats, one jet ski, and four rowboats. A medical doctor was stationed on board one of the motorboats, while a paramedic and a nurse were on standby at the beach base. The criteria for terminating the swim were based on either a voluntary request from the participant or an on-site judgment by the staff, including the medical doctor.

2.2. Study 2: Swimming VR Exposure Activity

Sixty-six healthy undergraduate students specializing in health and sports science participated in this study (44 males, 22 females; age: 18.1 ± 0.4 years). To simulate the physical sensation of swimming, subjects immersed their legs in water (30 °C) while being exposed to a VR of swimming off the coast using a head-mounted display (Meta Quest Pro). Measurements were taken during a 2-minute baseline period and a 2-minute VR exposure period. State anxiety was assessed using the State-Trait Anxiety Inventory (STAI) [15, 16] before and after the exposure.

Table 1. Sample characteristics.

-	Male	Female	Body Weight (kg)	Body Fat (%)	VO_2 Peak (ml/kg/min.)	400m Time (min' sec")
Group 1 (n=12)	9	3	62.3 ± 6.3	19.5 ± 9.5	47.1 ± 9.5	7'42" ± 1'08"
Group 2 (n=10)	8	2	64.6 ± 7.6	16.8 ± 5.2	46.8 ± 8.2	10'03" ± 0'25"
Group 3 (n= 7)	4	3	59.6 ± 9.1	17.1 ± 6.9	49.7 ± 9.2	11'45" ± 0'45" [a]
Group 4 (n= 6)	3	3	58.3 ± 4.7	21.3 ± 8.2	43.9 ± 7.3	15'21" ± 2'21" [b]
Group 5 (n= 5)	4	1	66.5 ± 11.8	12.6 ± 5.0	51.9 ± 4.8	14'31" ± 1'20" [a,b]

Note: * Data were expressed as the mean ± SD. Data marked with different superscripts showed significant differences ($p < 0.05$) according to the posthoc analysis using Kruskal-Wallis.

2.3. Ethical Considerations

Both Study 1 and Study 2 were approved by the Institutional Ethics Committee of Kawasaki University of Medical Welfare (Approval Nos. 23-046) and conformed to the Declaration of Helsinki. Informed consent was obtained from all participants *via* an opt-out method, which was deemed appropriate because the data were collected as part of a regular university curriculum (swimming training course); information was publicly disclosed, and participants were given the opportunity to decline the use of their data.

2.4. Statistical Analysis

Statistical calculations were performed using R (ver. 4.2.2) and RStudio. A two-way Analysis of Variance (ANOVA) followed by post-hoc Bonferroni tests was used for group comparisons. The relationship between swimming times and heart rate was analyzed using Pearson correlation coefficients. For VR data, paired T-tests or Wilcoxon rank-sum tests were used after normality confirmation. A p-value < 0.05 was considered significant.

3. EXPERIMENTAL SECTION

3.1. Real-time Monitoring System Architecture

A dedicated monitoring system was developed to ensure safety during long-distance swimming. The technical setup involved:

- Sensor Acquisition: Heart rate data was captured using a Polar Verity Sense sensor (Polar Electro, Kempele, Finland) positioned on the participant's temporal area.
- Data Transmission: Data was transmitted to a tablet PC on a monitoring boat following the swimmers.
- Base Station: The tablet relayed real-time data to a base station PC on the beach, allowing medical personnel to monitor physiological changes continuously.

3.2. Theoretical Calculation of Heart Rate Variability (HRV)

Autonomic nervous system activity was quantified using the MemCalc method [17]. The following frequency-domain indices were calculated from the HRV data:

- High Frequency (HF): 0.15 to 0.4 Hz, representing parasympathetic activity.
- Low Frequency (LF): 0.04 to 0.15 Hz.
- Normalization: For statistical validity, frequency components underwent natural logarithmic transformation (lnLF and lnHF).
- Sympathetic Index: The ratio of lnLF/lnHF was utilized as the primary index for sympathetic nerve activity.

4. RESULTS

4.1. Study 1: Real-time Heart Rate Monitoring in the Sea

The actual long-distance swimming time was 2 hours and 52 minutes (Fig. **1**).

The change in heart rate during long-distance swimming was significantly different between groups ($p < 0.001$, Fig. **2**).

There was no significant correlation between the 400m breaststroke time and VO_2 peak: estimated maximal oxygen uptake ($r = -0.10$, N.S., Fig. **3A**). There was a significant positive correlation between mean heart rate ($p < 0.01$, Fig. **3B**) and maximum heart rate ($p < 0.05$, Fig. **3C**) during distance swimming and the 400 m breaststroke time.

Two specific cases requiring rescue support were systematically analyzed (Table **2**, Fig. **4**). Subject A retired at 1 hour and 31 minutes. As shown in Figure **4A**, this subject exhibited a rapid heart rate increase to approximately 175 bpm around 10 minutes into the swim, sustaining this high rate for an hour before dropping out. Following rescue *via* jet ski, their heart rate decreased to approximately 80-100 bpm over 30 minutes. In another case, Subject B experienced hyperventilation, with their heart rate rapidly spiking from around 140 bpm to 170 bpm at approximately 10 minutes (Fig. **4B**). Staff immediately intervened by handing the subject a rescue tube, which resulted in a rapid heart rate recovery to approximately 140 bpm within 1 to 2 minutes.

Fig. (1). Course map of long-distance swimming. The blue line and markers on the map indicate the actual swimming trajectory of the subjects.

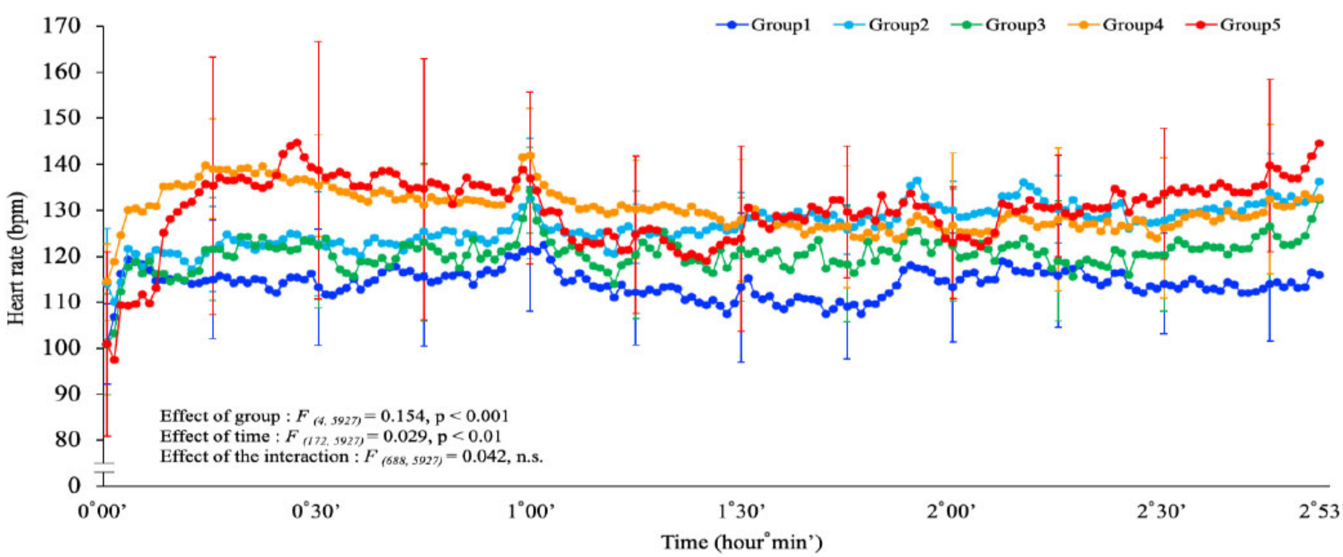

Fig. (2). Changes in absolute heart rate for each group during long-distance swimming. Data are shown as means. Error bars represent the 95% confidence intervals (CI), displayed at 15-minute intervals.

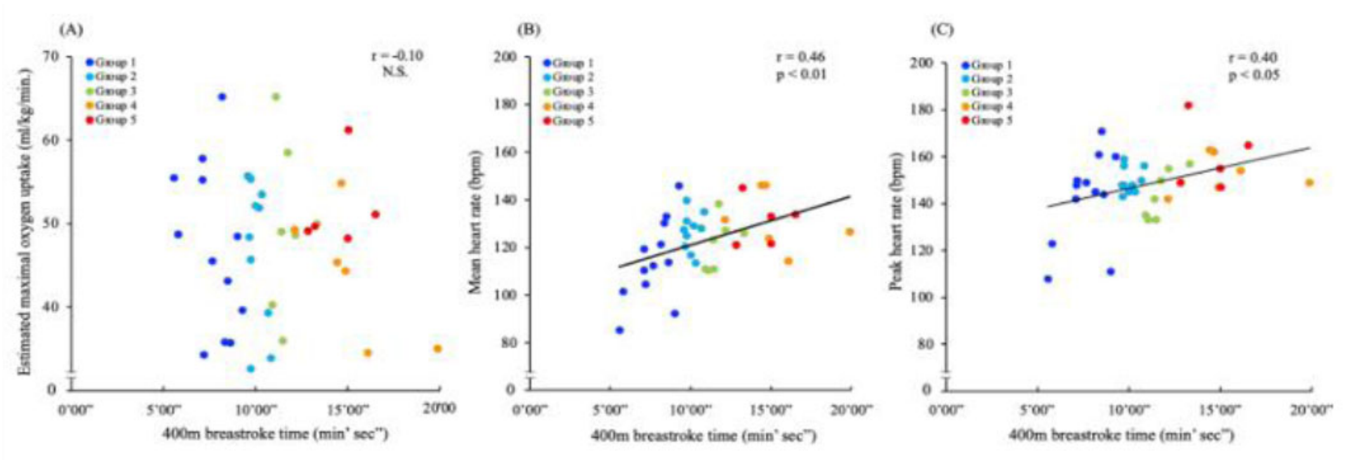

Fig. (3). Relationship between estimated maximal oxygen uptake **(A)**, mean absolute heart rate **(B)**, and peak absolute heart rate **(C)** during long-distance swimming, and the 400m breaststroke record.

Table 2. Detailed characteristics of the two cases requiring rescue support during long-distance swimming.

Subject	Baseline HR	Timing of HR Spike	Peak HR	Observed Symptoms	Intervention	Recovery Profile
Subject A	~90 bpm	At approx. 10 min	~175 bpm	Exhaustion (retired at 1h 31min)	Rescued by jet ski	HR decreased to ~80-100 bpm over approx. 30 min
Subject C	~80 bpm	At approx. 10 min	~170 bpm	Hyperventilation	Handed a rescue tube	HR rapidly recovered to ~140 bpm within 1-2 min

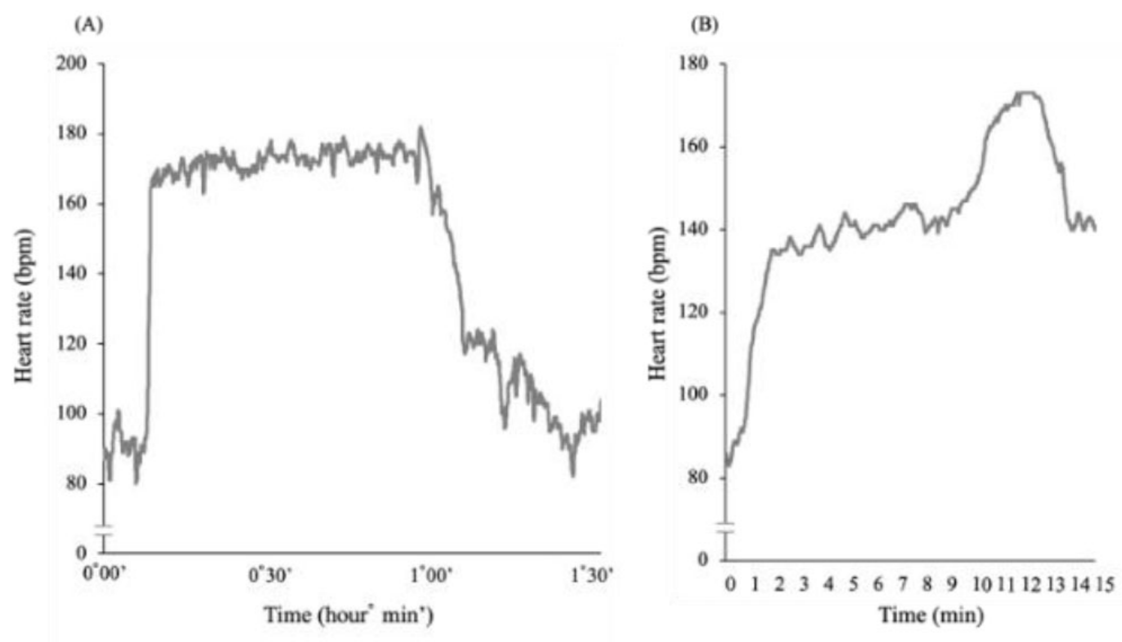

Fig. (4). Changes in absolute heart rate during long-distance swimming for two specific cases. **(A)** Heart rate trajectory of Subject A, who retired at 1 hour and 31 minutes. **(B)** Rapid heart rate increase observed in Subject B, who required support due to hyperventilation

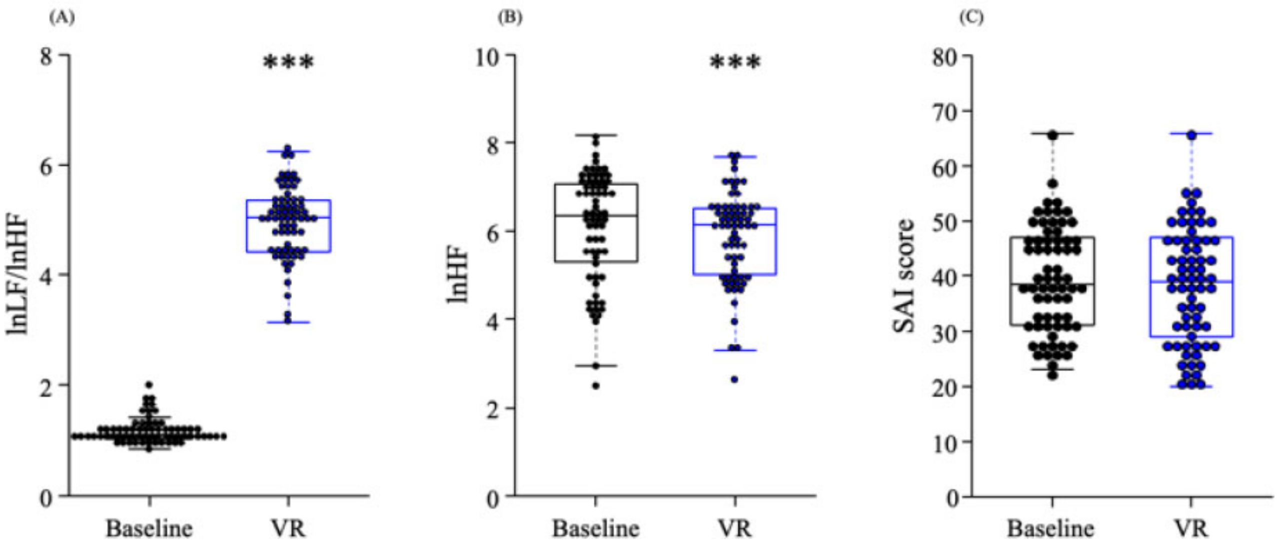

Fig. (5). Changes in cardiac autonomic nervous system indices (**A**: lnLF/lnHF, and **B**: lnHF) and State Anxiety Inventory (SAI) scores (**C**) in response to the swimming VR exposure. Data are shown as beeswarm and boxplots, where the central horizontal line represents the median, the box indicates the Interquartile Range (IQR), and the whiskers extend to 1.5 times the IQR. ***; $p < 0.001$.

4.2. Study 2: Cardiac Autonomic Nerve Activity Before and After Swimming VR Exposure

The measured heart rate during swimming VR exposure was not significant. The measured lnLF/lnHF of swimming VR exposure was significantly higher than baseline lnLF/lnHF ($p < 0.05$, Fig. 5A). Furthermore, lnHF showed significantly lower values ($p < 0.001$, Fig. 5B). No significant difference was observed in SAI obtained before and after swimming VR exposure (Fig. 5C).

5. DISCUSSION

The present study was the first to demonstrate a method for measuring and real-time monitoring of the heart rates of 40 individuals during long-distance swimming.

We observed significant differences in heart rate during the long-distance swim between the groups indicates that there were differences in heart rate associated with swimming ability. Furthermore, there was a significant correlation between the average and maximum heart rates during the distance swim and the 400m breaststroke time, indicating that changes in heart rate are swim ability dependent. The relationship between swimming ability and oxygen demand in the pool has already been shown [18], and similar results were shown for long-distance swimming in the present study. On the other hand, our results showed no correlation between estimated maximal oxygen uptake and swimming ability. This indicates that swimming ability in the sea is not dependent upon maximum aerobic fitness capacity.

In study 1, significant differences were observed in heart rate changes during the long-distance swim between the groups (Fig. 2). Particularly noteworthy was the rapid increase in heart rate during the first 30 minutes of the swim for groups 4 and 5, who had lower swimming ability, when compared with groups 1, 2 and 3. In fact, the subject who dropped out showed a change that increased to 170 bpm in 10 minutes, swam at 170 bpm for an hour, and then showed a decrease to about 80 bpm in about 30 minutes. Furthermore, another subject quickly increased their heart rate from 130 bpm to 170 bpm, and then was given a rescue tube. It was reported that triathlon fatalities in the United States from 1985 to 2016 showed a cardiac arrest incidence rate of 1.74 per 100,000 [19]. Most of these incidents (66.7%) occurred during the swimming segment [19]. Among the victims who underwent autopsy, cardiovascular abnormalities were identified in 44% of cases [19]. The two subjects in this study had no cardiovascular abnormalities. At the least, it appeared that monitoring rapid heart rate increases during the early stages of swimming could serve as a preliminary indicator to assist in detecting physiological abnormalities, potentially contributing to safer long-distance swimming. The study used data from students taking a swimming training course as undergraduates, rather than an experiment that forced them to experience danger. The previous study needs to be examined in detail, but it is very difficult to obtain data on the accidents that occurred. Therefore, we think that the data obtained in the two cases this time are important. However, further studies are necessary to validate these exploratory findings, especially before considering applications for children.

Since it is extremely difficult and rare to collect near-miss data during long-distance swimming in the sea, this study explored the feasibility of using VR as a safe alternative method to simulate a stress environment. We first examined changes in autonomic nervous system activity from a simulated experience under VR exposure.

Previous research has demonstrated that immersive VR scenarios can effectively induce and assess physiological regulation outcomes, including HRV, even within brief intervention windows [20]. It is known that LF/HF increases and HF decreases in response to acute stress [21]. We observed that the swimming VR exposure demonstrated the acute stress response. There was no difference in state anxiety scores obtained from the STAI before and after the swimming VR experience. This suggests that while the subjects may not have experienced conscious psychological anxiety, the observed changes in HRV likely reflect an unconscious, acute autonomic stress response to the simulated environment. It was reported that VR exposure for relaxation is associated with the decreasing LF/HF [22]. Accordingly, the study's result of high sympathetic activity depends on the swimming VR exposure. In the future, the use of VR for various scenes will need to be considered as preliminary data to predict reactions during long-distance swimming.

6. LIMITATIONS

This study has several limitations. First, peak oxygen uptake (VO_2 peak) was measured using a bicycle ergometer, which may not completely reflect actual swimming performance. Second, environmental factors in the sea (*e.g.*, waves, water currents) were not strictly controlled. Third, there is a potential risk of artifacts or noise when using the wearable device in a water environment. Finally, the VR exposure involved only the immersion of the legs, which does not fully replicate the actual physical experience of swimming in the sea.

CONCLUSION

The real-time heart rate monitoring system used in this feasibility study was applicable under calm conditions, and the data obtained showed a relationship between swimming ability and heart rate. Furthermore, swimming VR demonstrated potential as an exploratory method to safely observe physiological responses in simulated environments. However, while these are promising exploratory tools, their clinical value and application for anomaly detection require further validation.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: H.H.: Writing, original draft, project administration, methodology, investigation, funding acquisition, formal analysis, data curation and conceptualization; Y.N.: Editing, methodology, measurements, formal analysis and conceptualization; T.Ya.: Review, editing, methodology and measurements; T.T.: Review, editing, methodology, formal analysis and data curation; C.W., M.K.: Review, editing and measurements; E.O.: Review, editing and conceptualization; T.Yo., M.T., T.W.: Review & editing and methodology; M.J.K.: Writing, review and editing; H.M.: Writing, review, editing, methodology, formal analysis, data curation and conceptualization; H.Y.: Writing, review, editing, methodology and conceptualization. All authors reviewed the results and approved the final version of the manuscript.

LIST OF ABBREVIATIONS

HF	=	High Frequency
HR	=	Heart Rate
LF	=	Low Frequency
SAI	=	State Anxiety Inventory
STAI	=	State-Trait Anxiety Inventory
VO_2 peak	=	Peak oxygen uptake
VR	=	Virtual Reality

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study protocols were approved by the Institutional Ethics Committee of Kawasaki University of Medical Welfare (Approval numbers: 23-046). The research was conducted in accordance with the ethical principles of the Declaration of Helsinki. For both Study 1 and Study 2, informed consent was obtained *via* an opt-out method. Information regarding the study was publicly disclosed, and all participants were provided with the opportunity to decline the use of their data for research purposes. No participants exercised their right to opt out.

HUMAN AND ANIMAL RIGHTS

All procedures performed in studies involving human participants were in accordance with the ethical standards of institutional and/or research committees and with the 1975 Declaration of Helsinki, as revised in 2013.

CONSENT FOR PUBLICATION

Consent for the publication of research data was ensured through an opt-out process for all participants in Study 1 and Study 2. Participants were informed that the results of the study would be published in an academic journal, and they were given the opportunity to refuse the inclusion of their data. No participants refused the publication of their data.

STANDARDS OF REPORTING

STROBE guidelines were followed.

AVAILABILITY OF DATA AND MATERIALS

The data supporting the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available to protect the privacy of the participants.

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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