Assessing the Use of Heart Rate Monitoring for Competitive Swimmers

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ABSTRACT

Purpose: Quantifying training intensity provides a comprehensive understanding of the training stimulus. Recent technological advances may have improved the feasibility of using heart rate (HR) monitoring in swimming. However, the implementation of HR monitoring is yet to be assessed longitudinally in the daily training environment of swimmers. This study aimed to assess the implementation of HR by comparing the training intensity distribution from an external measure, planned volume at set intensities (PVSI), to the internal training intensity distribution measured using time in HR zones. **Methods:** Using a longitudinal observational design, ten competitive swimmers (8 males and 2 females, age: 22.0 ±2.3 yr, FINA point score: 842.9 ±58.5, mean ± SD) were monitored daily for 6-months. Each session, heart rate data, coached planned and athlete reported session rating of perceived exertion (sRPE; Modified CR10 scale) were recorded. Based on previously determined training zones from an incremental step test, PVSI was calculated using the planned distance and planned intensity of each swim bout. Training intensity distributions were analysed using a linear mixed model (lme4, R Core Team). **Results:** The model revealed a small-to-moderate relationship between PVSI and time in HR zone, based on the Nakagawa R squared value (range 0.14-0.42). **Conclusions:** Training intensity distribution differed between the internal measure (i.e., HR) and the external measure of intensity (i.e., PVSI). This demonstrates that internal and planned external measures of intensity cannot be used interchangeably to monitor training. Further research should explore how to best integrate these measures to better understand training in swimming.

Keywords: internal training intensity, planned external training intensity, wearable technology, training intensity distribution, swimming.

INTRODUCTION

The ability to effectively quantify training intensity is paramount in determining the effect of a given exercise bout[1]. Intensity can be described using an external measure (i.e., pace, velocity), or an internal measure (i.e., heart rate, blood lactate)[1]. Internal training intensity measures are preferred and thought to better reflect the pathophysiological response that drives adaptation[2]. In swimming, training intensity can be prescribed as a percentage of critical velocity[3], based on rating of perceived exertion (RPE)[4], or using a session goal time in zone approach[5]. Training intensity is also commonly prescribed as a distance swum at a predetermined velocity which is linked to a physiological anchor (i.e., a blood lactate value, heart rate range)[6,7]. This method of planned volume at set intensities (PVSI) provides a surrogate for internal intensity and assumes the corresponding internal physiological response to a prescribed velocity is consistently elicited. However, these methods are limited as without a continuous measure of actual exercise intensity, it is unclear whether the training session is eliciting the desired adaptations[2]. Therefore, other measures of intensity may provide a more comprehensive understanding of both the prescribed and actual training stimulus for swimmers.

Heart rate (HR) offers a practical, non-invasive, and inexpensive method of quantifying internal training intensity, and is used across a variety of endurance sports[8-10]. A major benefit of HR monitoring is its portability, allowing the internal training intensity to be continuously monitored in a range of training contexts, and the intensity distribution of the entire session to be captured. Despite their frequent use in land-based sports[8-10], the use of HR monitors to quantify time in HR zones in swim training has been limited[4,5]. This lack of implementation is most likely due to the challenges of measuring HR in an aquatic environment combined with the known limitations of HR monitoring (i.e., impact of hydration, temperature, limited ability to monitor high intensity interval training, assumed linear relationship between heart rate and oxygen consumption during maximal exercise)[11]. To circumnavigate this difficulty, previous studies have used non-waterproof HR monitors or manual palpation during swim training to capture HR measurements out of the water[12-14]. However, these approaches do not continuously measure intensity during an entire training session and may not completely reflect the training demands.

Recently, HR monitors using photoplethysmographic technology have been implemented in competitive swimming[6,15]. Whilst these monitors have been shown to be both valid and reliable in controlled settings[6,15], the feasibility of these units to quantify training intensity in the daily training environment is yet to be assessed. The purpose of this study was to assess the implementation of HR monitoring by comparing internal and planned external training intensity distributions in swimming. To do this, the association between PVSI and time in HR zone was assessed over the course of a season in highly trained competitive swimmers training in a high-performance environment.

METHODS

Subjects

Ten national-to-international level competitive swimmers [8 males and 2 females, age: 22.0 ±2.3 yr, FINA point score: 842.9 ±58.5, (mean ±SD)] were observed daily for 6-months. Written informed consent was obtained from the swimmers prior to the data analysis. Approval was obtained from the University of Technology Sydney Ethics Committee (ETH21-6130), and permission to use training data was granted by the provincial sporting institute. The investigation conformed to the Code of Ethics of the World Medical Association.

Design

A longitudinal observational design was implemented to examine the relationship between PVSI and time in HR zone. Athletes were monitored from January to June 2021 in the period leading up to a major national competition. Training sessions (~9 sessions/week) were completed in an indoor pool. The athletes attended three training camps, in outdoor training facilities, each lasting one-to-two weeks throughout the study period. These sessions were included in the analysis. During the study period, participants completed land-based strength training two times per week. Swimmers also competed in four competitions which were included in the total sessions but were excluded for analysis as athletes chose not to wear HR monitors while competing. Prior to each training session, the coach provided the planned distance and intensity of each swim bout using a modified PVSI method (see table 1) and a planned session rating of perceived exertion (sRPE; Modified CR10 scale)[16]. Each session, HR was recorded, and athletes reported their total distance swum and sRPE within 30 minutes of training completion. All participants were accustomed to these procedures as part of their ongoing training monitoring.

Methodology

Planned Volume at Set Intensities

Planned volume at set intensities were calculated by allocating the coach-prescribed swimming bouts into metres planned across 8 intensity zones. These zones were based on the descriptors used in Table 1[17,18] for zones 1-5. Three custom race pace zones (800-400 m pace, 200 m pace, 100 m pace and faster) were also calculated, these were individualised for each swimmer and based on a target time. Prior to analysis, all race pace work (800-100 m pace or faster) was combined into Zone 5 to align with HR-based training zones, where PVSI would represent metres swum in Zone 1 (Z1m) through to Zone 5 (Z5m) as shown in Table 1. Individual training zones were determined following an early season incremental 5 x 200 m step test[19]. The training intensity descriptors (see Table 1) were given to the athletes prior to the observation period to allow the athletes to individually relate to the training intensity zones. Training was then prescribed to the athletes as a volume, in metres, and a zone for example "400m at Zone 1 intensity". This method of training prescription was familiar to the coach and athletes as it formed part of their ongoing training monitoring.

Heart Rate

Swimmers recorded HR for all swim training sessions using the Polar OH1 HR monitor (Polar Electro, Kempele, Finland). The monitor was placed under the swimmers' swimming cap near the temple to record the entire training session[6,15]. At the end of each session each athlete uploaded the recorded session from their personal HR monitor to a secure online athlete monitoring system (Polar Flow; Polar Electro, Kempele, Finland; https://flow.polar.com). Each HR file was downloaded and assessed using a customised template (Microsoft Excel, Microsoft, Oregon USA). All HR files were checked and coded as a full session (HR data available for the entire session), a partial session recording (a session with any missing data), or a missing session (no HR data available). Partial sessions were included in the analysis if no more than 5% of data was missing. At the conclusion of the study, each athlete's peak HR across the data collection period was obtained from Polar Flow and used as the maximal physiological anchor point. The time in HR zones were calculated for each session. Zones were based on each athlete's peak HR (Z1 50-75%, Z2 75-80%, Z3 80-85%, Z4 85-92% and Z5 >92%)[17].

Session Rating of Perceived Exertion.

For all training sessions both the coach planned and athlete sRPE were recorded [16]. During the athletes' warm up the coach was asked to report each athlete's planned sRPE for the session. This was recorded in a customised Microsoft Excel spreadsheet (Microsoft Excel, Microsoft, Oregon USA). RPE_{diff} was calculated by subtracting the athlete reported sRPE from the coach planned sRPE, yielding a positive or negative RPE_{diff} value.

Statistical Analysis

For analysis, sessions with no or partial HR recordings were excluded, sessions with missing PVSI, sRPE or session that were modified data were removed and are shown in Table 2 as *missing training data*. The training intensity distributions from PVSI and time in HR zone were compared using linear mixed models (LMMs). Using time in HR zone as the dependent variable LMMs were constructed for each of the 5 zones using the *lme4* package in R (R Core Team). The time in HR zone (in seconds) was compared to the PVSI (in metres) for each intensity zone, with each zone examined independently (e.g., Z1 time in HR zone compared to Z1 PVSI, Z2 time in HR zone compared to Z2 PVSI, Z3 time in HR zone compared to Z3 PVSI, Z4 time in HR zone compared to Z4 PVSI, Z5 time in HR zone compared to Z5 PVSI). Given the repeated measures design, a null model was firstly specified using the individual athlete identifier as the random effect. The analysis model used PVSI and RPE_{diff} as fixed effects and the individual athlete identifier as the random effect. The distribution of the residuals was checked for normality using a QQ plot. Data are presented as the parameter estimate, the standardised mean difference 95% confidence interval and Akaike Information Criterion (AIC). The Nakagawa R squared value (R^2c) was calculated using the MuMIN Package in R to show goodness of fit in the LMM[20]. The magnitude of the Nakagawa R squared value was assessed using the following criteria; < 0.10; trivial; 0.10-0.29 small; 0.30-0.49, moderate; 0.50-0.69 large; 0.70-0.89 very large; and 0.90-1.00, almost perfect[21].

RESULTS

Missing Data

Throughout the observation period, 2001 training and racing sessions (mean duration 90.4 minutes) were captured across the 10 athletes (Table 2). Of those, 781 sessions were excluded from the analysis. Reasons for exclusion included missing training data, missing HR recordings, partial HR recordings, or racing sessions (Table 2). Table 3 provides further detail on the training sessions (based on athlete reported sRPE) that were missing HR data. There were 1220 individual training sessions included in the final analysis.

Linear Mixed Models

A summary of random effects, parameter estimates, model fit, and Nakagawa R squared values (R^2c) for the LMMs are shown in Table 4. The R^2c values ranged from 0.14 to 0.42 showing a small-to-moderate relationship between PVSI and time in HR zone (see Table 4). The AIC for the analysis model was higher than the null model for all zones and was accepted (see Table 4).

DISCUSSION

The present study aimed to assess the implementation of HR monitoring in competitive swimmers by comparing planned external and internal training intensity distributions. Our assessment of HR monitoring in a high-performance training environment highlighted a large amount of missing HR data (39%) when compliance checks and strategies to ensure monitor use were not utilised. When comparing planned external to internal load, the results of a LMM showed a small-to-moderate relationship between PVSI and time in HR zone across the five intensity zones. A main finding was the amount of missing data associated with longitudinal HR monitoring. Missing data can negatively impact the monitoring of training intensity and may introduce statistical biases when analysing training data[22]. Whilst the HR monitors used in the present study have been validated to measure maximal HR in swimming[15], the number of sessions with no HR recording (7.2%) or a partial HR recording (24.3%), reduced the feasibility of HR monitoring in the present study. Although, it should be noted that large inter-individual differences in the percentage of missing data (see Table 2) were observed. It is unclear whether the missing HR data in the present study was from technical or human sources.

Missing data from HR monitors due to technical problems in an aquatic environment have been reported[4,23] and placement under the swimmers' caps may have further disrupted the consistent detection of HR in the present study. Other studies have measured HR using monitors out of the water with non-waterproof HR monitors or using chest straps[6,13]. From a practical perspective, unexplained drop out may also occur due to athletes removing their HR monitor during the session, poor skin contact, loss of contact during dive starts, or low batteries. As a result, when implementing HR monitoring systems it would be beneficial to record the cause and source of missing data. Then develop strategies to mitigate its impact on training monitoring and improve the feasibility of using HR monitoring. Common strategies to overcome missing data include imputation of missing values through modelling or averages[24]. Practical strategies to reduce the amount of missing data could include, routine reminders to wear HR monitors, ensuring monitors are worn for the entire session and having spare HR monitors available. Alternatively, coaches and sports science practitioners may choose to prioritise the collection of main set data from their swimmers to ensure the key training stimulus of the session is captured. There was also a small number of sessions with missing RPE or PVSI data, or sessions that were modified due to athlete injury (9.8%) during the study period. This demonstrates the difficulty collecting data daily from all participants in an applied, ecological setting. Therefore, when implementing HR monitoring, coaches and sport science practitioners need to be aware of the potential sources of missing HR and training data to then develop practices to mitigate the occurrence.

The small-to-moderate relationship between PVSI and time in HR zone based on the R^2c value suggests a discrepancy between the assumed internal response using PVSI and the actual internal HR response. Previous research has also found mixed results relating internal and external measures of training intensity[25]. A study in open water swimming identified differences between internal and external intensity distributions using session RPE, session goal and time in HR zone, and distance[5]. During a season of cycling training, researchers have also reported large discrepancies between RPE, HR and power output during high-intensity training and moderate discrepancies between these variables at low intensities[10]. The authors suggested these discrepancies are due to the impact of HR lag (i.e., the delay or latency in HR response to a given workload at the onset of exercise) on time in zone as an intensity measure[10]. Moreover, HR lag may negatively impact HR monitoring in swimming more than cycling due to the high prevalence of interval training in swimming and is an inherent challenge when attempting to capture training intensities in both the aerobic and anaerobic domains using heart rate. In team sports, where interval training is common, differences between HR-based training measures and external measures have been reported[26,27]. In American football, where intervals can contain very high running speeds, HR data alone did not have meaningful correlations with external training intensity measures[27]. When derived into a HR-based intensity measure with duration (i.e., TRIMPs and HR reserve), there were only meaningful relationships with low-intensity external measures[27]. In soccer, the use of time in HR zone as an intensity measure was criticised as it underestimated physiological stress[26]. Accordingly, in the present study factors such as HR lag, may have impacted the relationship between PVSI and time in HR zone. Consequently, coaches and sport science practitioners looking to implement HR monitoring should be aware of these limitations and look to contextualise the HR data alongside other training variables (i.e., blood lactate measures or RPE) or explore other analysis options when implementing HR monitoring to assess high-intensity interval training.

Heart rate measures have a limited ability to reflect the relative intensity of high-intensity intermittent efforts[16]. In the present study, the relationship between time in HR zone and PVSI at high intensity (zone 5), was moderate ($R^2c = 0.42$). Given the lack of previous research on the longitudinal assessment of contemporary HR monitors in competitive swimming, it is difficult to contextualise our findings within the current swimming literature. Previous swimming research has documented the potential impact for HR lag[15] and suggested session-RPE may be more sensitive as a training intensity measure than HR during high intensity swim training[4]. In dry-land sports, research has demonstrated a similar discrepancy between HR-based measures of intensity and external measures of intensity[8,9,16,25-28]. Since race pace training is not centrally regulated, it is logical a small relationship may exist between PVSI and time in HR zone at high intensity. However, this does not explain why the relationship in zone 5 was higher than the other training zones in the present investigation. It is possible that this is due to combining both maximal aerobic and race pace efforts into a single training zone, or the relatively low volume of training completed in this zone[26]. Alternatively, it may be linked to the limited ability for HR to accurately monitor high-intensity training, and highlights the need for a multivariate approach to monitor intensity. As this is the first study to assess HR in swimming longitudinally, further research is required to better understand and explain the relationship between PVSI and HR at high intensities.

The small-to-moderate relationship between PVSI and time in HR zone may have been impacted by the inherent differences between internal and planned external subdimensions of training. In the present study, the PVSI measure, a distance at a predetermined velocity, was compared to the time spent in each HR zone, two different subdimensions of training load. Previous studies have found similar small relationships between internal and external training load and intensity measures[25-27]. In team sports, different monitoring methods, such as sRPE, HR measures and external velocity measures were shown to provide different information about a single training stimulus[29]. A key factor driving these differences may be the varied internal response experienced by athletes to a given external training load depending on their psychobiological state prior to the training session[2]. Given the complexity of physiological systems the likelihood of a single variable capturing the complexity of a single exercise bout is low[28,30]. Accordingly, there needs to be caution when monitoring training with a single measure[29], and when assuming an internal response from a planned external measure. The combination of several training monitoring variables in a multivariate approach has long been advocated for and the benefits previously demonstrated[4,12,28,29]. Furthermore, given that different training monitoring methods can influence the calculation of training intensity distribution[8], a multivariate approach may provide a more holistic description of completed training. For example, it may be advantageous to prescribe and monitor low-intensity (i.e., zone 1-4) bouts with HR to capture the cardiorespiratory centred training stimulus and use both RPE and velocity to reflect the demands of high-intensity training (i.e., zone 5). In endurance running, the use of running times has been suggested to more accurately reflect the sudden changes in velocity that come with high-intensity interval training[8]. Given the differences between internal and external sub-dimensions of training implementing a multivariate approach to training monitoring may assist in contextualising HR data. These monitoring approaches can assist in developing a deeper understanding of training and assist in improving training prescription practices for coaches and sport science practitioners.

A limitation of the present study was that only planned velocities, rather than actual velocities were measured. Understanding if the swimmers successfully achieved the prescribed velocities would have provided additional information to contextualise the HR data. As such, it is important for the results to be interpreted as the difference between internal training intensity and planned, rather than actual external training intensity. An additional limitation was the use of peak HR from the season with PVSI zones based on velocities from pre-season. These limitations may have reduced the amount of explained variance in the models and impacted our results. A further limitation was the large amount of missing HR data, which led to differences in the number of sessions analysed for each athlete and potentially biased the types of sessions analysed in the study. Finally, there are several considerations to be addressed when quantifying training in this cohort. In this study, training was completed in a range of environments (i.e., training camps, varying environmental conditions and 25 and 50m pools) which may have increased variation in the results. Future studies may look to assess the impact of these factors on the relationship between measures of training intensity.

PRACTICAL APPLICATIONS

The use of HR provides insight into the internal intensity experienced by swimmers during training. However, the current findings suggest when using HR data to quantify training intensity distribution, it should not be interpreted in a similar manner to when PVSI is used. This finding highlights the importance of continuing to use the pre-existing method(s) of prescribing and monitoring training when introducing a new method, such as HR monitors into a competitive training environment. Moreover, considering the limitations of each method of training monitoring, a multivariate approach incorporating both internal and external training intensity measures, could be adopted. Prescribing and monitoring training using HR-based measures of intensity for aerobic training and using RPE or PVSI-based methods for work above maximal aerobic capacity may help improve our understanding of athlete training. To ensure robust data collection when using HR monitors, an awareness of the sources of missing data (i.e., technological, or human error) should be established. Then, measures to account for the missing data, or to mitigate missing data in the first place should be implemented. By implementing these approaches coaches and sport science practitioners can gain a more comprehensive understanding of completed training, which can help support future training prescription.

CONCLUSION

Longitudinal HR monitoring can provide valuable insight into an athlete's internal response during training. Based on the current findings, strategies to minimise missing HR data may be needed within the training environment. Also, the small-to-moderate relationship between the planned external measure (PVSI) and the internal measure (time in HR zone) highlight that the two methods of training load monitoring cannot be used interchangeably. Coaches and sport science practitioners should consider implementing a multivariate approach to training monitoring using both internal and external measures of intensity to better understand the training. Future research should look to develop strategies to mitigate missing HR data, account for the potential impact of HR lag on training analysis and asses how HR monitoring can be implemented effectively in a multivariate approach to training monitoring.

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Figures and Tables

Table 1 Descriptors used to describe planned volume at set intensity. Adapted training zones from Jamnick, Pettitt, Granata, Pyne and Bishop [17]

Physiological anchor	**Z1 (m)**	**Z2 (m)**	**Z3 (m)**	**Z4 (m)**	**Z5 (m)**
$\%HR_{peak}$	50–75%	75–80%	80–85%	85–92%	> 92%
Blood lactate	< 2.0	2.0–2.5	2.5–3.5	3.5–5.0	> 5.0
RPE	<11	11–12	13–14	15–16	17-19

RPE - Rating of Perceived Exertion, *$\%HR_{peak}$* - percentage of peak heart rate, *Z1* - Zone 1, *Z2* - Zone 2, *Z3* - Zone 3, *Z4* - Zone 4, *Z5* - Zone 5

Table 2 Training characteristics of each participant throughout the data collection period including a summary of missing and excluded data.

Participants	Weekly Volume (km)	Total Swim Sessions	Full Recording	Partial Recording	No Recording	Racing Sessions	Missing Training Data	Partial Sessions Excluded	Total Included Sessions	% HR Data Included
Participant 1	38.63	209	60	104	20	25	20	60	98	47%
Participant 2	38.63	213	163	12	10	28	19	8	146	69%
Participant 3	36.79	208	128	47	7	26	25	18	135	65%
Participant 4	47.56	138	94	12	8	24	5	1	99	72%
Participant 5	37.98	203	108	50	23	22	18	28	116	57%
Participant 6	37.06	209	127	43	16	23	25	31	114	55%
Participant 7	50.89	220	160	31	3	26	17	6	171	78%
Participant 8	36.15	193	111	28	37	17	18	12	109	56%
Participant 9	41.83	209	120	50	13	26	28	32	115	55%
Participant 10	43.07	199	118	50	8	23	21	31	117	59%
Total		2001	1189	427	145	240	196	227	1220	61%

* Exclusion criteria for heart rate analysis are discussed in the methods. Sessions were excluded if >5% of heart rate data was missing, *HR*- heart rate, *km* – Kilometres,

Table 3 Number of sessions excluded based on athlete reported sRPE

Training Zone	Number of sessions excluded based on athlete reported sRPE
Z1	37
Z2	44
Z3	20
Z4	25
Z5	64

sRPE – Session Rating of Perceived Exertion, *Z1* - Zone 1, *Z2* - Zone 2, *Z3* - Zone 3, *Z4* - Zone 4, *Z5* - Zone 5

Table 4 The parameter estimated and 95% confidence intervals for the null model and the analysis model for each of the 5 zones for the relationship between planned volume at set intensities and time in heart rate zone.

	Random effects				Fixed effects								Model Fit	
	Between Participant Differences						Planned Volume at Each Set Intensity (m)			RPE_{diff}				
Models	Intercept	SD	Residuals	SD	Intercept	95% CI	Estimate	95% CI	SMD	Estimate	95% CI	SMD	AIC	R^2c
						Zone 1								
Z1 null model	238240.00	488.10	928778.00	963.70	3957.60	(3617.61, 4296.96)							20267.60	0.20
Z1 model	**237387.00**	**487.20**	**850615.00**	**922.30**	**3510.00**	**(3159.23, 3860.60)**	**0.21**	**(0.16, 0.25)**	**<0.001**	**143.00**	**(95.09, 190.89)**	**0.29**	**20165.20**	**0.27**
						Zone 2								
Z2 null model	27289.00	165.20	217397.00	466.30	617.52	(500.81, 734.64)							18489.20	0.11
Z2 model	**28208.00**	**168.00**	**194764.00**	**441.30**	**404.10**	**(281.29, 527.00)**	**0.11**	**(0.09, 0.13)**	<0.001	**31.24**	**(8.32, 54.15)**	**0.18**	**18360.40**	**0.21**
						Zone 3								
Z3 null model	19447.00	139.50	192378.00	438.60	394.10	(295.70, 493.72)							18338.00	0.09
Z3 model	**18272.00**	**135.2**	**182571.00**	**427.30**	**312.89**	**(214.79, 411.40)**	**0.16**	**(0.12, 0.20)**	**0.001**	**26.73**	**(4.54, 48.92)**	**0.20**	**18278.10**	**0.14**
						Zone 4								
Z4 null model	29800.00	172.60	155019.00	393.70	253.87	(378.54, 409.95)							18080.60	0.16
Z4 model	**25218.00**	**158.80**	**137764.00**	**371.20**	**194.49**	**(83.05, 306.22)**	**0.43**	**(0.36, 0.50)**	**0.002**	**6.71**	**(−12.66, 26.08)**	**0.04**	**17940.20**	**0.24**
						Zone 5								
Z5 null model	2942.00	54.24	29055.00	170.46	60.36	(21.70, 98.98)							16031.90	0.09
Z5 model	**1591.00**	**39.89**	**18137.00**	**134.68**	**−5.60**	**(−34.45, 23.43)**	**0.22**	**(0.21 ,0.24)**	**0.006**	**−16.48**	**(−23.62, −9.35)**	**-0.41**	**15495.70**	**0.42**

Significance determined as $p \leq 0.05$, *AIC* - Akaike's information criterion, **Bold** = best model fit, CI - confidence interval, *m* – Metre, R^2c – Nakagawa R squared value, RPE_{diff} – Difference between athlete reported and coach planned rating of perceived exertion, *SD* - Standard deviation, *SMD* - Standardised mean difference