Perceived Exertion, Time of Immersion and Physiological Correlates in Synchronized Swimming

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Key words
- synchronized swimming
- RPE
- blood lactate
- heart rate
- apnea
- water immersion

Abstract

This study examined the relationship between ratings of perceived exertion (RPE, CR-10), heart rate (HR), peak blood lactate (La_{peak}), and immersion (IM) parameters in 17 elite synchronized swimmers performing 30 solo and duet routines during competition. All were video recorded (50 Hz) and an observational instrument was used to time the IM phases. Differences in the measured variables were tested using a linear mixed-effects model. RPE was 7.7 ± 1.1 and did not differ among routines, and neither did any of the HR parameters. There were differences among routines in La_{peak} ($F_{3,7} = 16.5$; $P = 0.002$), number of IM ($F_{3,15} = 14.0$; $P < 0.001$), total time immersed ($F_{3,16} = 26.6$; $P < 0.001$), percentage of time immersed ($F_{3,13} = 6.5$; $P = 0.007$) and number of IM longer than 10 s ($F_{3,19} = 3.0$; $P = 0.04$). RPE correlated positively to HR pre-activation, range of variation and recovery, IM parameters and La_{peak}, and inversely to minimum and mean HR. A hierarchical multiple linear regression (MLR) model (number of IM > 10 s, HR recovery, minimum HR, and La_{peak}) explained 62% RPE variance (adj. $R_m^2 = 0.62$; $P < 0.001$). A stepwise MLR model (La_{peak}, mean IM time and pre-exercise HR) explained 46% of performance variance (adj. $R_m^2 = 0.46$; $P < 0.001$). Findings highlight the psycho-physical stress imposed by the combination of intense dynamic exercise with repeated and prolonged apnea intervals during SS events.

Introduction

The ultimate goal of sports is to produce a winning or personal best performance at a specific time during competition. Monitoring the internal load, i.e., the acute physiological response induced by exercise on the athlete, is crucial for understanding the physiological and mental requirements for sporting success. Furthermore, internal load monitoring is a key component of the training process for the purpose of setting the optimal dose-response relationship between training stress and adaptation. In modern synchronized swimming (SS), performances depend on advanced water skills and require great strength, endurance, flexibility, grace, artistry and precise timing, as well as exceptional breath control when upside down underwater [18]. As a result, training requirements at the elite level often result in high-volume (averaging about 40 h per week) and high-intensity training programs [41]. As such, elite synchronized swimmers need to engage in a well-designed and balanced training program, to optimize performance and to reduce the risk of overtraining, burnout and injury [40,41].

Several studies have addressed the physiological responses during different types of SS training such as figure execution [20,23,24], routine elements [56,60] and simulated competitive routines [5,12,28,44] with the aim of quantifying the internal training load. However, the addition of acrobatic elements, the increase in movements speed, the complexity and difficulty of routines, the synchronization to each other (in duet and team events), as well as the fact that swimmers spend almost 50% of the routine time underwater [23] have made it difficult to monitor swimmers' physiological parameters during competition. Additionally, the use of such physiological measures in training sessions on a daily basis is often limited by the lack of appropriate equipment and the fact that training needs to be interrupted to obtain these measurements [46]. For these reasons, coaches usually monitor the training process based on the administered external load (e.g., number and duration of training sessions, type and number of elements, sets and repetitions) despite the fact that the same external load can elicit different physiological responses and training adaptations, depending on the athlete's age, fitness and skill level [7].

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Table 1 Characteristics of participants.

	All swimmers (n=17)
height (cm)	165.1±6.3
body mass (kg)	52.4±5.5
age (years)	17.9±3.5
training (h·week^{-1})	37.4±6.4
sports-specific practice (years)	9.8±3.1

Values are mean±SD

In this context, the rating of perceived exertion (RPE) appears to be a useful tool for prescribing exercise intensity based on its relationship with physiological indicators including lactate, heart rate (HR) and oxygen uptake. A RPE is based on the understanding that athletes can inherently monitor the physiological stress their bodies experience during exercise, and thus be able to adjust their training intensity using their own perceptions of effort [48]. The validity thereof has been claimed for different modes of exercise such as running, rowing, cycling and swimming with the use of the aforementioned physiological measures as criteria [13]. Furthermore, several attempts have been made to study physiological correlates with perceived exertion during sports competition [10,54]. Unfortunately, however, little is known concerning aesthetic sports such as SS. Based on the findings that SS requires high levels of aerobic and anaerobic endurance [28] due to the very demanding exercises, lasting about 2–5 min (FINA; Synchronized swimming rules; [Internet]; [cited 2012 Dec 5]; Available from: http://www.fina.org/), the Category-Ratio (CR-10) Scale [8] appears to be one of the best choices, not only regarding its psychometric characteristics and criterion-related validity [13] but also for being especially useful in measuring anaerobic efforts [42]. Given these advantages, it seems logical to explore the utility of RPE as a holistic assessment tool for monitoring internal load in SS.

The utility of using submaximal RPE to quantify training load has been widely tested in aquatic disciplines such as swimming [30,46,58] and acrobatic diving [37], with our group having recently published descriptive data on SS during competition [49]. Elite synchronized swimmers are exposed to hypoxia because of the combination of breath holding during IM periods and vigorous exercise [14]. There has been very little previous research on the effects of hypoxia on perceived exertion. Shephard et al. [55] stated a distorting influence of hypoxia if respiratory sensations are used to "fine-tune" an exercise prescription. Chen et al. [13] in a recent meta-analysis reviewed the criterion-related validity of Borg's RPE scales in healthy individuals, suggesting that, even if not explaining a high proportion of the variance in RPE scores, respiration rate might be the best indicator of physical exertion (R=0.72) compared to ventilation (R=0.61), $\dot{V}O_2$ (R=0.63), blood lactate concentration (R=0.57) and HR (R=0.62). Homma [23] reported that the time of IM in international SS competitions was different according to the event: solo (62.2%), duets (56.1%) and teams (51.2%). Based on differences in recovery HR, La_{peak} and RPE, Rodríguez-Zamora et al. [49] reported that solo and duet competitive events, were physically more demanding than team routines, and that free routines were generally more so than technical programs. Viewing these results collectively, it seems plausible to think that the perception of effort in SS could be influenced by apnea due to IM.

Therefore, the aims of this study were (a) to evaluate whether RPE would be an appropriate tool for assessing the internal load in competitive SS and determining the relationships between RPE and the physiological response during the most demanding SS events; (b) to verify whether there is a relationship between immersion periods and RPE; and (c) to determine which parameters can explain the perceived exertion in competitive SS. The hypothesis was that RPE in SS is influenced by duration and/or frequency IM periods of the routines, with the concomitant impact being on the relationships between RPE and the physiological response. A secondary hypothesis is that bradycardia due to the diving response has a significant effect on swimmers' perceived exertion.

Methods

Participants

17 synchronized swimmers, including swimmers from the Spanish national junior and senior teams – among them Olympic (n=7), and junior (n=10) World Championships medalists – volunteered for the study. Each had competed on the national and international level at least in the previous 2 years. All subjects voluntarily participated in the study and provided written informed consent, with parental permission when needed. The study was conducted according to the requirements stipulated in the Helsinki Statement [22] and approved by the Ethics Committee for Clinical Sport Research of Catalonia. Participants' primary physical and training level characteristics are shown in **Table 1**.

Study design

The study was conducted at the 2011 Spanish National Winter Synchronized Swimming Championships, a qualifying event for participation in the London 2012 Olympic Games. All routines were performed during the competition with the ad hoc approval of the Refereeing and Organizing Committees of the Royal Spanish Swimming Federation. Most swimmers performed in more than 1 event, having a minimum 2-h rest period between each, and are thus included in more than 1 program.

The study protocol is summarized in **Fig. 1**. Routines (n=30) were performed in a 50-m indoor pool (water temperature 25–26 °C) with 30 m available for use. Each swimmer performed a coach-prescribed standard warm up within their scheduled time frame. Capillary blood samples were taken from the earlobe following a 5-min passive rest interval and immediately before the call to perform. After warming up the swimmers dressed in their competition suits and were advised to keep warm but not to exercise heavily. Heart rate (HR) monitors were placed on each swimmer's chest before the warm-up and removed 10 min after the routine was executed. Each routine was assessed and marked by the official judges of the competition according to FINA rules (FINA. Synchronized swimming rules; [Internet]; [cited December 5, 2012]; Available from: http://www.fina.org/), and total competition scores (TCS) were awarded.

Procedure and instrumentation

Rating of perceived exertion: The Borg CR-10 category-ratio scale was chosen for rating the perceived intensity of exertion [8]. A graphical, colored, verbally anchored scale was shown to the swimmers immediately after they completed the routine and were aware of the TCS. The week before competition, all participants were assessed repeatedly during at least 3 training ses-

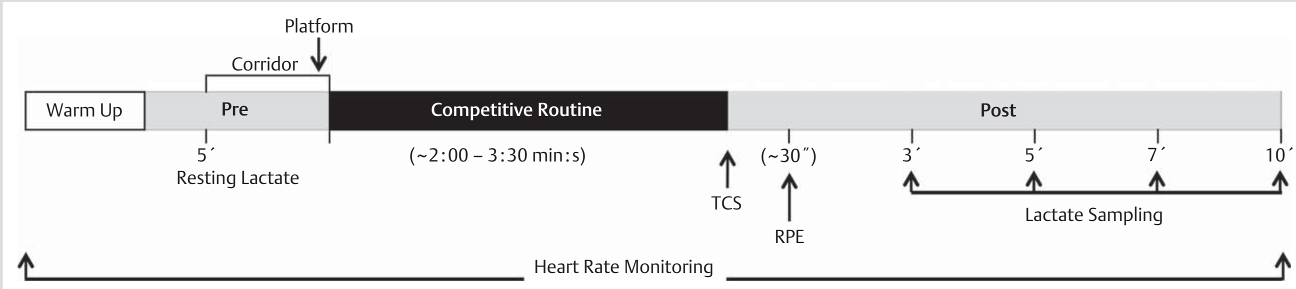

Fig. 1 Study protocol TCS: total competition score; RPE: rating of perceived exertion; Corridor and platform: swimmers' location at the pool.

sions to disclose learning effects [46] and to improve the consistency of the measurements during competition.

Heart rate monitoring: HR was measured beat-by-beat using waterproof monitors (CardioSwim, Freelap, Fleurier, Switzerland). To minimize potential instrumentation bias, swimmers wore the HR monitor during training sessions within 1 week before competition. HR was assessed from R-R intervals, 1-s interpolated, and smoothed by computing a running average for 5-s intervals using a 1-s window. HR_{pre} is the average HR for the minute immediately before the start of the routine, after the specific warm-up, and following a 5-min recovery interval. HR_{peak} and HR_{min} are the highest and lowest 1-s value during the exercise, while HR_{mean} is the mean for the whole competitive routine, and HR_{range} is the difference between HR_{peak} and HR_{min} values during the routine. Heart rate recovery was determined with HR_{post1}, HR_{post3}, and HR_{post5} being mean recovery HR at minutes 1, 3 and 5 [45].

Blood lactate: At every competitive session 10 µl of capillary blood were drawn from the earlobe following warm-up and a 5-min recovery period and before the call to perform. Sampling was repeated 3, 5, 7 and 10 min after the routine as it has been shown to be an adequate time span for detecting post-exercise peak lactate accumulation in blood in SS athletes [49]. Capillary samples were analyzed using a calibrated lactate photometer (Diaglobal DP100, Berlin, Germany). The highest value was taken as the peak post-exercise lactate concentration (La_{peak}).

Video recording and observational instrument: Each routine was video recorded using a digital video camera (Panasonic AG-DVX100BE 3-CCD Mini-DV Cinema Camcorder) at 625-line/50 Hz PAL interlaced video mode. The stationary video camera was placed at an elevated site by the pool, located 1 m away from the edge, just in front of the judges' podium, and perpendicular to the midpoint of the 30-square meter area available for competition. The professionally operated camera recorded each swimmer's actions during the competitive routine, including the TCS announcement. A central computer timer was used for time synchronization of the video and HR and transmitting beacon signals. This was done by filming the timer displayed on the computer screen, and recording the HR monitor activation time on the same computer. Recorded images were decoded and registered with specific free software (LINCE, version 1.1, Barcelona, Spain) [17]. Data were registered and evaluated according to the following immersion (IM) phases: face in (complete facial IM, chin and forehead included); face out (non IM or partial IM, not including the forehead) [52]. The following IM parameters were computed for all routines for each swimmer: the number of times the swimmer immersed her face (NIM), the total (TIM) and the mean time of immersion (MIM), the percentage of the routine duration in which the swimmer had her face immersed (RIM %), the longest time of immersion (IMmax), the number of immersions longer than 10 s (NIM > 10 s) and the total time spent immersed for longer than 10 s (TIM > 10 s). For the purpose of this analysis, IM periods were considered when the swimmer's face was immersed, i.e., she was holding her breath or exhaling underwater with her forehead underwater. Inter- and intra-observer reliability was determined in four routines by two expert coaches and researchers who had previously been trained in using the observation instrument. Cohen's kappa values were above 0.90 in all cases.

Performance: According to FINA rules (FINA. Synchronized swimming rules; [Internet]; [cited 2012 Dec 5]; Available from: http://www.fina.org/), the entire performance time of each routine was set as follows: technical solo (TS), 2 min; free solo (FS), 3 min; technical duet (TD), 2:20 min:s; and free duet (FD), 3:30 min:s (± 15 s were allowed in each performance). TCS for technical routines is composed of separate scores for execution and overall impression, while for free routines TCS is composed of separate scores for technical merit and artistic impression. In both cases, TCS is up to a maximum of 100 points.

Statistical analysis

Because of the unbalanced design and the existence of intra-subject correlated data (most swimmers participated in more than one routine), a linear mixed-effects model (restricted maximum likelihood method) was used to compare group means among routines (TS, FS, TD, and FD). Pairwise comparisons with Bonferroni correction were used to identify significant differences between pairs of estimated means. Pearson's correlation coefficients were calculated between RPE and each studied variable for the entire group of swimmers. First, an exploratory algorithmic multiple regression analysis (MLR) was conducted (stepwise selection) with RPE as dependent variable and primary physiological and IM parameters as predictor variables ($P_{in} = 0.05$, $P_{out} = 0.10$). After checking for collinearity among predictor variables and after considering their partial correlation coefficients and tolerance levels, a hierarchical MLR analysis was performed to construct an explanatory model of RPE scores as the predicted variable. The same procedure was followed for TCS as predicted variable. Results are presented as mean ± standard deviation (s). Statistical analyses were conducted using PASW Statistics for Windows (v.18; SPSS Inc., Chicago, IL). Precise P-values are reported, and $P < 0.05$ was considered significant (bilateral).

Table 2 Perceived exertion and heart rate response during synchronized swimming competitive routines.

	Technical solo (n=5)	Free solo (n=6)	Technical duet (n=10)	Free duet (n=9)	All routines (n=30)
RPE (a.u)	7.0±0.4	7.9±0.4	7.4±0.3	7.9±0.4	7.7±1.1
HR_{pre} (bpm)	123.8±4.5	139.1±5.3	126.2±3.2	128.5±5.2	127.2±12.0
HR_{min} (bpm)	92.4±11.4	85.0±12.4	95.7±8.4	83.0±11.7	87.7±28.1
HR_{mean} (bpm)	154.0±6.4	158.5±6.9	159.7±4.7	158.6±6.5	157.1±15.3
HR_{peak} (bpm)	196.2±4.6	187.7±5.0	188.7±3.4	194.8±4.7	191.1±10.5
HR_{range} (bpm)	103.6±12.2	104.9±13.6	94.1±8.9	101.3±12.9	103.4±27.2
HR_{post1} (bpm)	144.7±8.1	152.2±9.8	159.1±5.7	161.7±9.5	154.4±18.1
HR_{post3} (bpm)	106.5±5.0	111.6±6.0	113.8±3.5	129.7±5.8	118.1±13.6
HR_{post5} (bpm)	88.4±5.3	106.7±5.6	105.0±3.6	110.4±5.3	103.0±13.5

Values are means ± SD; RPE: rating of perceived exertion score; a.u.: arbitrary units (0–10+); HR: heart rate; bpm: beats · min^{-1}; HR_{pre}: mean HR for the last minute before the start of the routine, after warm-up and a 5-min recovery period; HR_{peak} and HR_{min}: highest and lowest 1-s value during the exercise; HR_{mean}: mean for the whole competitive routine; HR_{range}, HR_{peak} minus HR_{min}: values during routine; HR_{post1}, HR_{post3}, HR_{post5}: post-exercise HR at minutes 1, 3, and 5 of recovery

Table 3 Post-exercise peak blood lactate and immersion time parameters in synchronized swimming competitive routines.

	Technical solo (TS) (n=5)	Free solo (FS) (n=6)	Technical duet (TD) (n=10)	Free duet (FD) (n=9)	All routines (n=30)
La_{peak} (mmol · L^{-1})	7.6±0.5	6.7±0.5	5.9±0.5††	7.9±0.5*	7.0±1.8
NIM (times)	17.1±1.9	26.4±2.2†	21.0±1.3	33.3±2.1*	24.4±6.9
TIM (s)	82.7±3.9	105.3±4.6†	85.0±2.8††	125.1±4.5*	100.1±18.8
MIM (s)	5.0±0.3	4.2±0.3	4.1±0.2	4.1±0.3	4.3±0.9
RIM% (% of routine duration)	69.5±2.3	57.9±2.6†	58.7±1.7††	60.7±2.4	61.2±6.0
IMmax (s)	19.6±1.8	23.1±2.1	18.8±1.3	22.6±1.9	20.6±4.1
NIM > 10 s (times)	2.9±0.5	4.0±0.6	3.9±0.3	5.2±0.6*	4.1±1.3
TIM > 10 s (s)	45.2±7.0	63.7±8.4	53.5±5.0	76.6±8.2	61.1±18.0

Values are mean ± SD; La_{peak}: post-exercise peak blood lactate; NIM: number of immersions; TIM: total time face immersed; MIM: mean immersion time; RIM%: percentage of routine duration; IMmax: longest time of immersion; NIM > 10 s: number of immersions longer than 10 s; TIM > 10 s: total time immersed for longer than 10 s. Significant differences among routines (P < 0.05, see text for precise P-values) are:
La_{peak}: *vs. TD, ††vs. TS
NIM: *vs. TD and TS, †vs. TS
TIM: *vs. FS, TD and TS, ††vs. FS, †vs. TS
RIM%: ††vs. TS, †vs. TS
NIM > 10 s: *vs. TS

Results

RPE, physiological responses and immersion parameters

RPE scores for all routines (7.7 ± 1.1) ranged from 6 ("hard-very hard") to 10 ("extremely hard"), and did not differ among the four different routines (▶ **Table 2**). Likewise, the pattern of the HR response was not different among routines for any of the studied parameters (▶ **Table 2**).

Differences were noted among routines in La_{peak} (▶ **Table 3**) ($F_{3,7}$ = 16.5; P = 0.002), with lower values in TD (5.9 ± 0.5 mmol · l^{-1}) than in TS (7.6 ± 0.5 mmol · l^{-1}; P = 0.01) and FD (7.9 ± 0.5 mmol · l^{-1}; P = 0.003). ▶ **Table 3** also shows the IM parameters during the competitive routines. No significant differences were observed among routines in MIM, IMmax and TIM > 10 s. NIM was higher in FD (33.3 ± 2.1 times) than in TD (21.0 ± 1.3 times; P = 0.001) and TS (17.1 ± 1.9; P < 0.001) and also higher in FS (26.4 ± 2.2) than in TS (17.1 ± 1.9 times; P = 0.003) ($F_{3,15}$ = 14.0; P < 0.001). Differences were also observed in TIM ($F_{3,16}$ = 26.6; P < 0.001), with higher values in FD (125.1 ± 4.5 s) than in FS (105.3 ± 4.6 s; P = 0.006), and in both technical routines (P < 0.001), TD (85.0 ± 2.8 s) and TS (82.7 ± 3.9 s). Differences were also noted in RIM% ($F_{3,13}$ = 6.5; P = 0.007), which was higher in TS (69.5 ± 2.3 %) than in TD (58.7 ± 1.7 %; P = 0.004) and FS (57.9 ± 2.6 %; P = 0.02). Finally, TS (2.9 ± 0.5 times) showed lower NIM > 10 s than FD (5.2 ± 0.6 times; P = 0.04) ($F_{3,19}$ = 3.0; P = 0.04).

RPE and immersion correlates

RPE positively correlated to several immersion parameters (TIM > 10 s: R = 0.61; P < 0.001; TIM: R = 0.58; P < 0.001; NIM > 10 s: R = 0.50; P = 0.003; NIM: R = 0.33; P = 0.04; and RIM%: R = 0.31; P = 0.05), La_{peak} (R = 0.50; P = 0.003), and some HR parameters [HR_{range} (R = 0.45, P = 0.006), HR_{post3} (R = 0.44; P = 0.008), HR_{post5} (R = 0.45; P = 0.006), and HR_{pre} (R = 0.37; P = 0.02)]. Furthermore, RPE scores inversely correlated to HR_{min} (R = −0.53, P = 0.001) and HR_{mean} (R = 0.38; P = 0.02). However, neither HR_{peak} (R = −0.26; P = 0.09) nor HR_{post1} (R = 0.07; P = 0.36) correlated to RPE. ▶ **Fig. 2** shows the regression graphs for RPE vs. some of those variables (TIM > 10s, La_{peak}, and HR_{min}).

Since there was evidence that RPE scores were associated with various physiological and IM parameters, a MLR analysis was performed to determine which variables played the most significant role in explaining RPE variance. The exploratory algorithmic MLR analysis (stepwise procedure) produced a best-fit model (R_m^2 = 0.80; adj. R^2_m = 0.50; SE_E = 0.69; $F_{3,27}$ = 14.5; P < 0.001) that included TIM > 10 s, HR_{min} and HR_{post5} (beta coeff. 0.46, −0.39 and 0.31, respectively) and can be described by the following equation:

$$RPE = 4.878 + 0.027\,TIM>10\,s - 0.015\,HR_{min} + 0.024\,HR_{post5} \quad (1)$$

For the hierarchical MLR analysis it was decided to additionally introduce La_{peak} considering its high correlation with RPE

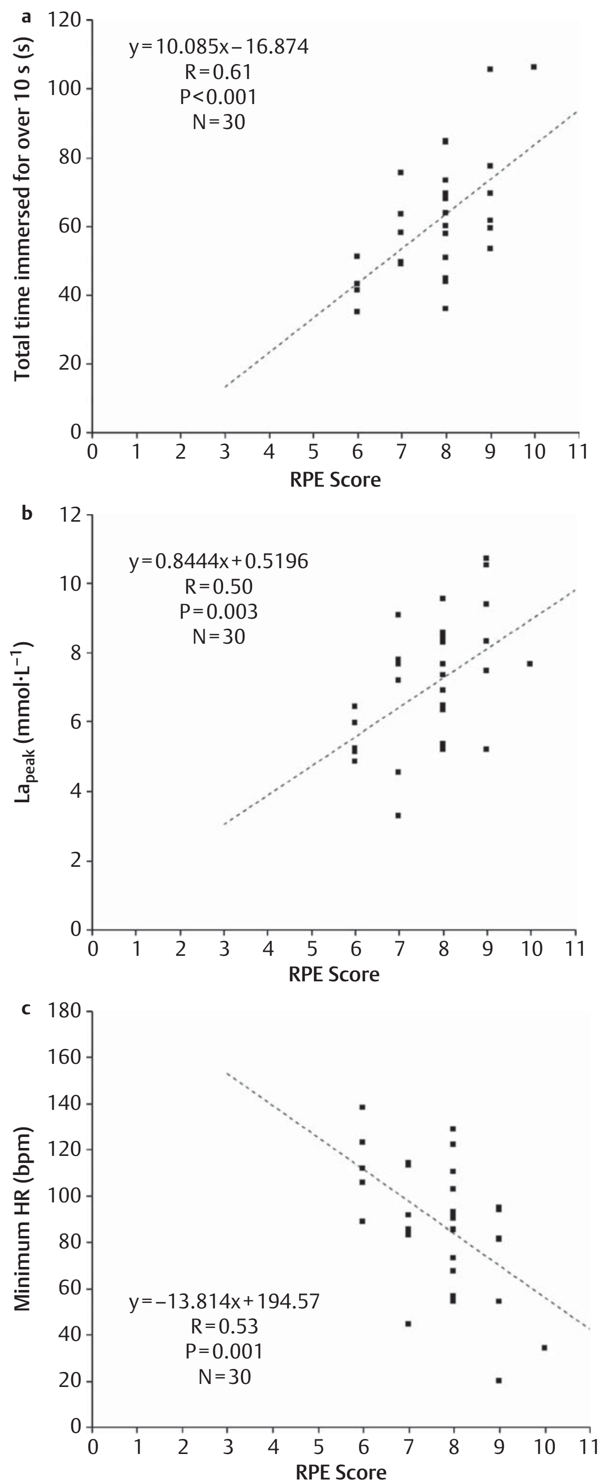

Fig. 2 Linear Regression Regression analysis between RPE scores and **a** total time immersed for longer than 10 s (TIM > 10 s) during the routine, **b** peak post-exercise lactate concentration (La_{peak}) and **c** minimum heart rate during the routine (HR_{min}). Linear regression equations and Pearson's correlation coefficients (R) are shown.

(R = 0.50, P = 0.003) and its fair tolerance level (0.88), although it ended up not being a significant predictor (beta coeff. 0.30). This explanatory model ($R_m^2=0.79$; adj. $R^2_m=0.62$; $SE_E=0.72$; $F_{4,25}=10.1$; P < 0.001; beta coeff. 0.41, 0.29, −0.31 and 0.15, respectively) can be described as:

Table 4 Significant correlations between performance (TCS), and physiological and immersion parameters during synchronized swimming routines during competition.

	TCS (points)	
	R	P-value
La_{peak} (mmol · L^{-1})	0.55	0.002
Heart rate parameters (bpm)		
HR_{pre}	−0.37	0.047
Immersion parameters		
NIM (times)	0.39	0.033
MIM (s)	−0.50	0.005
IMmax (s)	0.48	0.007

TCS: total competition score; La_{peak}: peak blood lactate concentration; HR: heart rate (bpm); HR_{pre}: mean HR for the last minute before the start of the routine, after warm-up and a 5-min recovery period; NIM: number of immersions; MIM: mean immersion time; IMmax: longest time of immersion; R: linear Pearson's correlation coefficient

$$RPE = 4.232 + 0.025\ TIM > 10\,s + 0.023\ HR_{post5} - 0.012\ HR_{min} + 0.090\ La_{peak} \qquad (2)$$

Performance correlates

▶ **Table 4** reports linear correlation coefficients between competitive performance (TCS) and physiological parameters and IM parameters. TCS positively correlated with La_{peak} and 2 immersion parameters (NIM and IMmax), and inversely correlated to MIM and HR_{pre}. A stepwise selection MLR model included three predictor variables: La_{peak}, MIM, and HR_{pre} ($R_m^2=0.72$; adj. $R^2_m=0.46$; $SE_E=4.64$; $F_{3,26}=9.07$; P < 0.001; beta coeff. 0.424, −0.325, and −3.15, respectively). The best-fit hierarchical explanatory MLR model including all correlated variables (MIM, NIM, La_{peak}, IMmax, and HR_{pre}) slightly improved the predictive strength of the model ($R_m^2=0.78$; adj. $R^2_m=0.53$; $SE_E=4.33$; $F_{5,24}=7.44$; P < 0.001; beta coeff. −0.59, −0.44, 0.43, 0.37, −0.20, respectively), although IMmax, and HR_{pre} were not significant predictors (P > 0.05).

Discussion

This study evaluated the adequacy of RPE in assessing the internal load in competitive SS in relation with the physiological responses during the most demanding SS events during competition. Our results suggest that the independent use of RPE to determine exercise intensity may underestimate the degree of physiological strain in sports such as SS. In addition, the use of the CR-10 RPE scale does not appear to be a good tool for monitoring the internal load if peak lactate or peak HR alone are taken as criterion variables. The present findings confirmed the initial hypotheses of a significant relationship between RPE and the cardiovascular response during exercise and recovery, the frequency of longer immersions and the peak blood lactate concentration during competition, which explained 62 % of the variance in RPE scores.

RPE, physiological responses and immersion parameters

RPE has been defined as the subjective intensity of effort, strain, discomfort, and/or fatigue that is experienced during physical exercise [47]. As in previous reports both during competition [49] and training [61] present results show that elite synchronized swimmers perceive exertion during competitive routines as "hard-very hard" to "extremely hard", with no significant differences existing among technical and free solo and duet events.

The somewhat greater scores obtained (+9.1% on average) compared to our previous report [49] can be explained by the exclusion of the team events in that study, which were found to elicit lower RPE values compared to solo and duet events. It was then suggested that the lower RPE in the team events could be due to the lower rate of skill elements (32.2%) [24], the lower blood lactate levels attained [28,49,60], and the shortest number of apnea periods [23].

It is noteworthy that no differences were found among routines despite their different duration (from about 2 min in the TS to about 3:30 min:s in the FD). This can be explained by the fact that athletes with a moderate fitness level perceive exercise to be relatively more strenuous and feel that they can continue for less time than high-fitness level athletes at comparable relative intensities, reflecting an effect on perceived exertion for a given relative exercise intensity, whereas there is no effect for a given relative exercise duration [19].

RPE, physiological responses and immersion correlates

With respect to the possible IM influence on RPE, characteristics of the routines settings would influence perceptual responses to exercise as reflected by the fact that technical programs elicited lower RPE values than free events despite almost equal cardiovascular response (▶ **Table 2**). The reason for this disparity could be explained by the nature of the routines, as the rules favor prolonged immersions in the free programs. According to FINA rules (FINA; Synchronized swimming rules; [Internet]; [cited 2012 Dec 5]; Available from: http://www.fina.org/), the technical routines are composed by mandatory elements, executed in a specific order representing 70% of the score, with the remaining 30% for the overall impression. However, in the free programs there are no restrictions, thus giving more merit to exercise difficulty and variety of movements, as well as to synchronization, creativity and originality. Both Davies et al. [14] and Alentejano et al. [1] support this concept as they reported a tendency for the free programs to start with the longest possible underwater sequence, which may last in excess of 45 s in the case of more highly placed contestants [14].

It is worth noting that, similarly to RPE, none of the HR parameters studied differed significantly between events (solo, duet and team) nor programs (technical and free). The HR response was characterized by intense anticipatory pre-activation and rapidly developing tachycardia up to maximal levels, with interspersed periods of marked bradycardia during the exercise bouts performed in apnea [49]. While apnea and facial immersion causes HR reduction [32,51], exercise increases sympathetic stimulation of the heart and increases HR [26]. Thus, when the swimmer starts holding her breath during the exercise, both inputs compete with each other for control of HR [59] and O_2 flow to the exercising muscles, though the O_2 conservation diving response would finally prevail until the swimmer is able to breathe again [49]. This would be in accordance with previous findings showing that cardiovascular demands of SS competitive routines can be described as very high, regardless of the duration, technical content, category – junior (15–18 years) and senior (≥18 years), and condition – during training [28,44,56] and competition [49]. This fact would play a role in the specific adaptation to this particular physiological condition by routine repetition-based training as previously suggested [2,3,49].

It has been suggested that the inputs for RPE can be categorized into those of central and local origin [43]. Central factors thought to be linked to RPE are the sensations primarily associated with the cardiorespiratory system resulting from tachycardia, tachypnea and dyspnea. Sensory input for RPE of local origin produce the sensation of strain in the working muscles and joints and arise from stimuli of chemically and mechanically sensitive receptors in skeletal muscles, tendons and joints [62]. It is worth noting that local factors supply the primary perceptual input at low to moderate exercise intensities, while central factors dominate at higher intensities [43]. In competitive SS routines, obviously pertaining to the latter, the opposed chronotropic influence of intense exercise (positive) and frequent and long immersions (negative) are accompanied by strong tachypneic and dyspneic neural stimuli after the IM intervals, which can be assumed to be directly proportional to its duration and to the intensity of the exercise involved in apnea.

The hypothesis that prolonged and frequent immersions would result in increased RPE, and that the central factors would elicit higher RPE values, is supported by the finding that, despite technical programs (TS, TD) being shorter than free programs (FS, FD), the longest immersion time (IMmax), the number of the longest immersions (NIM > 10 s) and their duration (TIM > 10 s) were actually found in the free programs (▶ **Table 3**). It is well documented that immersions of the swimmers' heads, with the concomitant apnea and stimulation of the cold-receptors of the upper part of the face, elicits the diving response [52]. This is characterized by selective vasoconstriction and HR reduction (bradycardia) the magnitude of which is often used to estimate the overall magnitude of the response [16,32]. An additional explanation would be that the most rated exercise figures would imply more repeated and longer IM periods, thus eliciting more frequent and intense bradycardic episodes. This concept is supported by the observation that, while the solo event is composed of more figure parts implying a higher physiological stress than duets (51.9%) and teams (32.2%) [23,24], the events' IM percentages reported by Homma (1994) [23] – solo (62.2%), duets (56.1%), and teams (51.2%) – would be in accordance with the rated figure execution mentioned above.

According to our results, and given these observations, the less frequent and longer apnea periods would explain the lower perception of effort in teams compared to solos and duets [49]. Thus, the responsible mechanism of the RPE in SS appears not to be primarily related to the highest HR values attained but rather to the lowest HR during the exercise as a consequence of long apnea periods.

A unique aspect of SS is the frequent and often lengthy breath-holding periods while performing high-intensity exercise underwater. As previously mentioned, this aspect of the sport elicits the diving response [16,21] with the concomitant bradycardia [27]. Several studies have shown that facial cold stimulation without apnea causes a bradycardia similar in magnitude as during apnea alone [16,25,34]. The effects of respiratory arrest and facial cold stimulation appear to be additive, where a combination of both causes the strongest diving response [4,16,25,34,51]. Furthermore, the chilling of the forehead results in a more pronounced bradycardia than that obtained when other facial areas of similar size are chilled [53]. This has indicated that the receptors involved in triggering the response are located mainly in the forehead, or are more densely distributed in the forehead than in other parts of the face [53]. The results from this study are consistent with these observations since free programs elicited lower HR_{min} values than technical events (▶ **Table 2**) and bradycardia (HR_{min}) negatively correlated to RPE while being the second best predictor of RPE (▶ **Fig. 2**).

On the other hand, metabolic fatigue seemed to also play an important role in the perceived exertion in our swimmers, as reflected in the moderate relationship with post-exercise La_{peak} (R = 0.50; P = 0.003). Even if La_{peak} is closely related to RPE, it may be the case that, as in apneic diving, lactate removal from working muscles may be compromised by selective vasoconstriction, and restricted blood flow may lead to considerable regional differences in lactate concentration [50]. Along these lines, Joulia et al. [29] indicated that post-apnea and also post-exercise blood acidosis and the production of oxygen free radicals were attenuated in trained breath-hold divers. Similarly, Yamamura et al. [60] reported that it could be beneficial for synchronized swimmers to undergo lactate tolerance training to improve hydrogen ion buffering. In other terms, subjects involved in a long duration training program of breath-hold diving would show reduced blood acidosis and oxidative stress as a result of an adaptive mechanism to repeated apnea.

Multivariate analysis also provided new insights into the mechanisms involved in the perception of effort in SS. The algorithmic approach to MLR analysis (Eq. (1)) resulted in a compact model to predict RPE based on only three variables (TIM > 10 s, HR_{min}, and HR_{post5}), the first 2 reflecting the influence of long immersions and the subsequent bradycardia, and the third reflecting the slower HR recovery due to a possible training adaption in this type of athlete [3]. It is known that a faster response in post-exercise HR recovery reflects a positive adaption to exercise training and possibly performance capacity in endurance events [57]. Additionally, it has been reported that trained synchronized swimmers exhibited longer breath hold periods with similar physiological responses but at a lower HR during recovery in comparison to women who are not trained in breath holding [3]. Thus, synchronized swimmers would be less affected and recover quicker from breath holding and exercise compared to controls [3]. At this point a plausible explanation to this observation can be suggested, where the exaggerated diving response and superior apneic ability would be a result of their training adaptation to apnea [2], affecting the perception of effort and, hence, RPE scores. This seems to be consistent with our observation that RPE values were significantly higher in juniors than in seniors after competitive SS routines [49] and corresponded to a tendency for reporting lower post-exercise HR recovery values in seniors than juniors. On the other hand, given that swimming performance is strongly related to energetic profile [6], we believe that the hierarchical approach (Eq. (2)), where La_{peak} was included among the predictor variables, even if it not significantly increasing the predictive capacity of the model (62 % vs. 60 % of the RPE variance), offers a better explanatory view of the main factors involved in the perception of effort in elite SS, where blood lactate accumulation represents a peripheral metabolic mediator. Considering all these factors, and taking into account the results, where RPE scores positively correlated to most IM parameters (particularly to TIM > 10 s, NIM > 10 s and TIM, reflecting long and frequent immersions) and inversely correlated to minimum (▶ **Fig. 2c**) and mean HR (both reflecting the influence of intense and frequent bradycardic episodes), it seems reasonable to assume that the long and frequent IM and their impact on HR as a result of the diving response have strongly influenced the RPE. This would be further supported by the strong positive correlation found between RPE and HR_{range}, which indicates the range of variation between maximum (i. e., exercise induced) and minimum (i. e., strongest diving reflex bradycardia) HR. The lack of a significant (or perhaps negative) association of RPE with maximum HR (R = −0.26; P = 0.09) might indirectly indicate that bradycardia has a greater influence on the perception of effort than tachycardia in SS exercise. In short, the more frequent and intense the apneic episodes and the more intense and frequent the diving response-induced bradycardic epochs, the greater the perceived effort.

Performance correlates

Although the relationship between selected physiological parameters and performance have been previously reported in a large sample of elite synchronized swimmers [49], this is the first report in which IM parameters have been related to performance. In our previous report, HR_{pre} and HR_{min} explained 26 % of variability in performance (TCS), supporting the idea that an augmented diving response is associated with higher performance in SS [49]. In this study, 46 % of TCS variance could be predicted by La_{peak}, MIM, and HR_{pre} and raised to 53 % by adding NIM and IMmax (i. e., number of and longest IM during the routine). The greater HR decrease for the highest performing swimmers, reflected in the relationship between TCS and the number of immersions (NIM), and longest time of immersion (IMmax) (▶ **Table 4**), suggests that best swimmers show a greater adaptation to breath holding, which would likely translate into a more efficient O_2 conservation effect [2]. In summary, the higher the lactate, the number of immersions and longest IM time, and the lower the mean time immersed and the pre-exercise HR, the better the performance during competition. This finding is in line with the coaches and judges' idea that, in addition to the very important aesthetic components, the higher intensity and the more frequent and longer immersions would be associated with higher merit and performance results.

Regardless of the potential mechanisms involved, the findings of this study suggest that the independent use of RPE to determine exercise intensity may underestimate the degree of physiological strain in sports such as SS. The independent use of the CR-10 RPE scale does not appear to be a good tool for monitoring the internal load if peak lactate or peak HR alone is used as criterion variable. However, the fact that recovery and minimum HR and repeated long immersions explained 62 % of the variance in RPE suggests that combined HR and RPE monitoring can be more sensitive to changes in internal workload than any of these methods alone or than poolside lactate assessments.

Limitations of the study

Certain issues and limitations regarding the design, methodology and overall validity of this study need to be considered. To preserve the ecological and external validity of the design, it was decided to conduct an observational field study during a real competition, a national championships qualifying for the London 2012 Olympic Games. Hence, there were restrictions imposed by the official rules to measurements that would not disturb the athletes and the competition itself, e. g. HR monitoring, post-exercise blood lactate concentration and RPE, and video analysis. Previous studies had pointed out relatively high reliability and validity coefficients between physiological variables and RPE (CR-10 scale) [36, 37, 39, 54]. Moreover, it has been shown that a very good prediction of subjective increase may be obtained by combining 2 simple variables from a work test, e. g., peak HR and blood lactate [9]. Among the relationships between perceived exertion and physiological variables studied here, those with HR might be of the greatest practical importance because both parameters are commonly used to assess the training internal load imposed by exercise. An important practical limitation in this design was the reliability of the HR measurements. A total of 56 routines were recorded, while only 30 could ultimately be used for analysis due to low quality recordings or failure of the waterproof monitors, most likely caused by the very intense movements during the routines and the suboptimal technical design for such demanding environmental conditions. There is definitely room for technical improvement in this kind of waterproof devices for research and monitoring purposes. Concerning blood lactate, certain limitations beyond the interpretative challenges already discussed must be acknowledged regarding the exact sampling time in those cases when the athletes were kept by the pool waiting for marking. To control this, we discarded measurements exceeding a reasonable delay (more than ~1 min).

Other points of concern were related to time-motion analysis. First, based on Match Vision Studio 3.0 software [11], LINCE has been designed to improve its software utilities in the time-action analysis of sports events using an observational methodology in naturalistic contexts. Second, specific criteria had to be established for data analysis. On the one hand, the IM phase in this study was defined as a complete immersion of the swimmers' face (chin and forehead included). This criteria seemed to be appropriate as the 2 main sensory inputs eliciting the diving response [16, 21] have been described as facial neural activity and cessation of respiratory movements [15]. The cessation of breathing *per se* leads to a reduction in stretch-receptor activity which initiates the diving response [16, 32]. In humans as in animals, the initiation of bradycardia at the onset of apnea is a result of interactions between the respiratory center and the cardiac autonomic centers in the central nervous system [31]. Thus, there is no difference in the bradycardic response between face IM apnea and whole body IM apnea [38]. On the other hand, IM periods greater than 10 s were chosen as longer periods based on the only time motion study in SS, which reported that soloists spent 46 % of the routine in IM over 6.8 s [1]. Finally, the potential effects of body position on the cardiovascular changes during apnea [33] must also be considered. For instance, Martins et al. [35] found that HR acute response was dependent on the type of motor skill, at least in infant swimming. However, the relative importance of body position to cardiovascular response in SS and how this could affect to RPE is an area that has yet to be investigated. Regarding the external validity of the design, it must be considered that only elite athletes were monitored. It has been reported that the degree of bradycardia tends to be higher in synchronized swimmers who are skilled and experienced [24]. Thus, to elucidate how the cardiovascular response could affect RPE in other populations (e.g., age categories and lower level competitors) would require further investigation involving cohort groups.

Conclusions

The study shows a significant association between the rating of perceived exertion and the frequency and duration of immersions, the magnitude of subsequent bradycardic events, the blood lactate accumulation, and the HR recovery during competitive SS routines. Prolonged and frequent immersions combined with intense exercise explain changes in perceived exertion, with cardiorespiratory factors providing a relatively greater neural input as compared to metabolic factors. Viewed collectively, these findings highlight the great psycho-physical stress imposed by the unique combination of intense dynamic exercise with repeated and prolonged breath-holding intervals during SS competitive events.

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