Physiological responses and competitive performance in elite synchronized swimming

Lara Rodríguez Zamora

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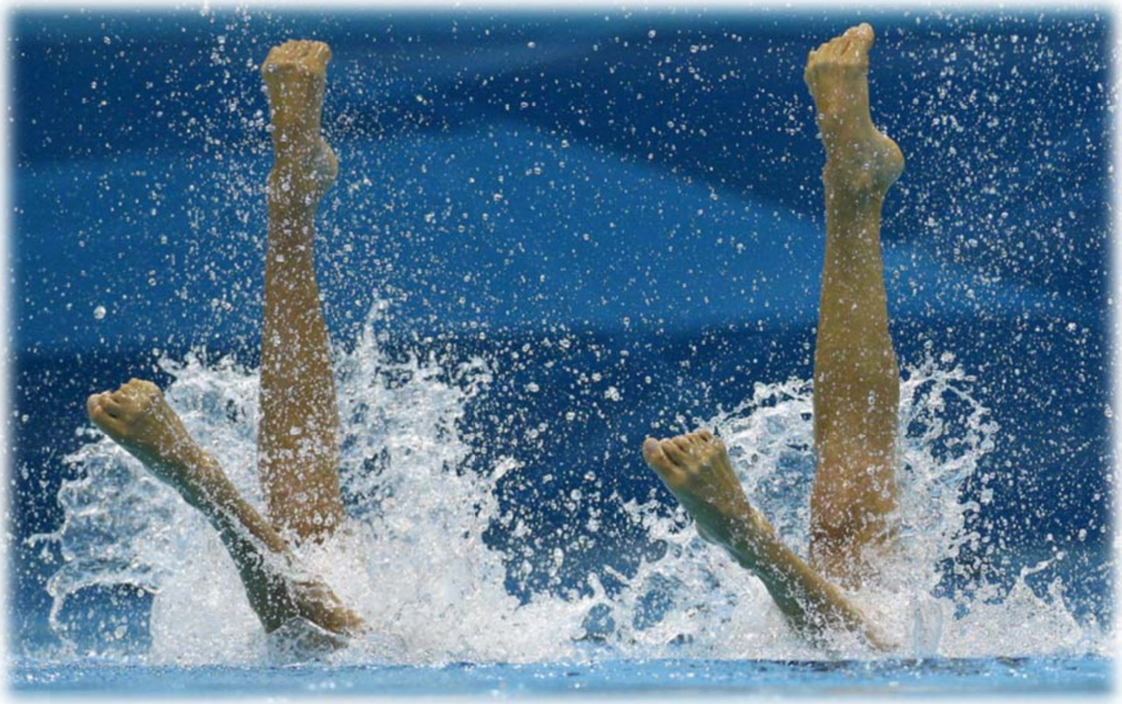

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Front cover picture: Ona Carbonell Ballestero and Andrea Fuentes Fache from Spain compete during the women's duet synchronized swimming free routine at the Aquatics Centre in the Olympic Park during the 2012 Summer Olympics in London, Monday, Aug. 6, 2012. Photography by Michael Sohn

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Lara Rodríguez Zamora

Directors / *Supervisors*

Prof. Xavier Iglesias Reig

Prof. Ferran A. Rodríguez Guisado

Programa de Doctorat "Activitat Física, Educación Física i Esport"

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Lara Rodríguez Zamora

Institut Nacional d'Educació Física de Catalunya — Centre de Barcelona
Spain
Telephone +34 630457006

Worrying does NOT empty tomorrow of its sorrow

It empties today of its strength

- *Corrie Ten Boom* -

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ABSTRACT

Previous research investigating synchronized swimming (SS) from a physiological perspective has mainly used figures or fractionated and/or simulated routine protocols during training, although the nature of this sport leads to continuous, very demanding exercises (~2-4 minutes) performed at increasingly higher levels of intensity with almost 50% of this time underwater. In addition, different from training, competition is a challenging situation which usually stimulates higher psycho-physiological responses in the participant. Current knowledge is thus limited as regards physiological responses in competitive elite SS. Therefore, the overall aim of this dissertation is to investigate the physiological responses related to performance during the execution of competitive routines both during training and competitive sessions in elite synchronized swimmers. The dissertation is based on three studies (Studies I-III); all of them use the same protocol with continuous cardiovascular monitoring during the competitive routines, perceived exertion assessment after the executions, and blood lactate measurements (Study I and III). Study I characterized the physiological responses in relation to performance during an official competition. In Study II the execution of the duets in both conditions—training and competitive session—was used to compare the athletes' internal load in order to ascertain whether swimmers may achieve the competitive intensity during training sessions, and Study III was performed to investigate how immersion periods, with the concomitant bradycardic events, affects perceived exertion with both physiological (HR) and subjective perceptual markers (RPE).

The current thesis demonstrates that cardiovascular responses during competition are 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 (Studies I–III). During competitive routines, moderate blood lactate accumulation suggested the activation of the glycolytic metabolism in the exercising muscles and an adaptive metabolic response due to the specific training adaptations in this kind of athletes (studies I and III). Furthermore, competitive routines were perceived as very to extremely intense by all swimmers, likely reflecting not only the absolute exercise demands but also their previous experience and expectations (Studies I – III). In Study II, the internal load (HR and RPE) imposed by SS duets performed during training was virtually identical to that elicited in a real competitive situation due to the effects of automaticity—embodied through the replication of the same movement sequence in practice—, and by the swimmers' long-term adaptations to specific routine exercise and apnea. There was a strong positive relationship between RPE and the duration and/or frequency of bradycardic events during routines (Studies II and III). In fact, the frequency and duration of immersions, the magnitude of subsequent bradycardic events, the blood lactate concentration, and the HR recovery during competitive SS routines explained 62% of the variance in perceived exertion, with cardiorespiratory factors providing a relatively greater neural input as compared to metabolic factors (Study III).

Attending the relationships between physiological parameters and performance, the magnitude of anticipatory heart rate activation and bradycardic response explained 26% of variability in performance (Study I). In Study III this percentage rose to 53% when immersion parameters and the lactate concentration in blood were related, supporting the idea that an augmented diving response is associated with higher performance in SS. The results presented on this thesis suggest that the higher intensity and the more frequent and longer immersions would be associated with higher merit and performance results (I and III).

Keywords: Apnea, breath holding, blood lactate, competition, diving response, heart rate, immersion, rating of perceived exertion, routine, synchronized swimming, training, elite athletes.

LIST OF PAPERS

This dissertation is mainly based on the following papers, herein referred to by their Roman numerals:

Paper I	Rodríguez-Zamora L, Iglesias X, Barrero A, Chaverri D, Erola P, Rodríguez FA. Physiological Responses in Relation to Performance during Competition in Elite Synchronized Swimmers. PLoS ONE, 2012;7(11):e49098.
Paper II	Rodríguez-Zamora L, Iglesias X, Barrero A, Torres-Ronda L, Chaverri D, Rodríguez FA. Monitoring internal load parameters during competitive synchronized swimming duet routines in elite athletes. J Strength Cond Res. (Accepted for publication 2013).
Paper III	Rodríguez-Zamora L, Iglesias X, Barrero A, Chaverri D, Irurtia A, Erola P, Rodríguez FA. Perceived exertion, time of immersion, and physiological correlates in synchronized swimming. Int J Sports Med. 2013.

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ABREVIATIONS

BH	Breath holding
CNS	Central nervous system
CO_2	Carbon dioxide
FS	Free solo
FD	Free duet
FT	Free team
HR	Heart Rate
HR_{pre}	HR for the minute immediately before the start of the routine
HR_{peak}	The highest HR 1-s value during the exercise
HR_{min}	The lowest HR 1-s value during the exercise
HR_{range}	Difference between the lowest and the highest HR value during exercise
HR_{mean}	Arithmetic HR mean for the competitive routine
HR_{post1}	Post-exercise HR are the average at minutes 1
HR_{post3}	Post-exercise HR are the average at minutes 3
HR_{post5}	Post-exercise HR are the average at minutes 5
IM	Immersion
IM_{max}	Longest time of immersion
La_{peak}	The highest post-exercise blood lactate concentration
MIM	Mean immersion time
NIM	Number of immersions
NIM>10	Number of immersions longer than 10 s
O_2	Oxygen
RIM%	Percentage of the routine with the face immersed
RPE	Ratings of perceived exertion
SS	Synchronized swimming
TCS	Total competitive score
TIM	Total time of immersion
TIM>10s	Total time of immersion longer than 10 s
TS	Technical solo
TD	Technical duet
TT	Technical team

TABLE OF CONTENTS

INTRODUCTION

Synchronized swimming

Synchronized swimming (SS) is a sports discipline that combines swimming, dancing and gymnastics. Synchronized swimmers perform a choreography called routine which consists of elaborate moves in the water accompanied by music. According to the number of swimmers competing at the same time, the SS routines can be categorized in three events — solo (one swimmer), duet (a couple) or team (eight swimmers). SS is governed by the Fédération Internationale de Natation (FINA) and was first introduced to the Olympic program as a demonstration sport in 1948. It became part of the official Olympic program in 1984, initially in the solo and duet modes, but dropped in 1996 in favor of team competition, and reintroduced in duet competitions at the 2000 Olympic Games. In each competitive session, swimmers competing above junior level must perform both a technical and a free program.

The technical routines are composed of 6–10 required elements selected every four years. They are performed in a specific order and last 2 min in the technical solo (TS), 2:20 min:s in the technical duet (TD) and 2:50 min:s in the technical team (TT). The free routines allow more flexibility to demonstrate grace, artistry and creativity, as there are no figure requirements. Their duration is 3 min in the free solo (FS), 3:30 min:s in the free duet (FD), and 4 min in the free team (FT) (39).

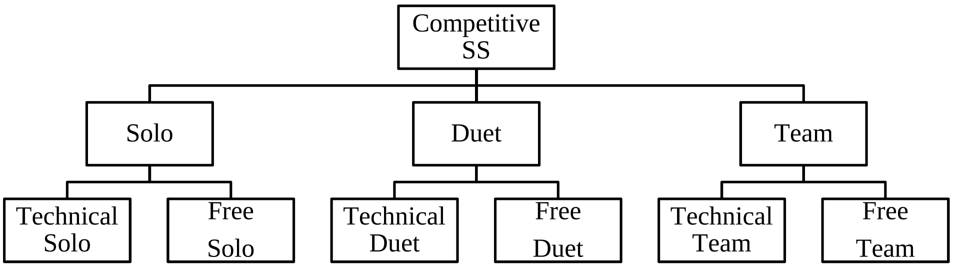


Figure 1. Competitive program in elite synchronized swimming. The combination routine has not been included in this investigation.

It should be pointed out that another free routine, the combo (combination routine), in which ten synchronized swimmers perform a free choreography lasting 5 min, is included in the competitive program of international competitions as well as in the World Championships. However, combo has not been studied in the investigation.

In SS, the total competition score (TCS) is awarded by two judging panels. For the technical routines, TCS is composed of separate scores for execution and overall impression and for free routines the TCS is composed of separate scores for technical merit and artistic impression. The execution and technical merit score rates the technical execution of all moves, including aspects such as the height of the body out of the water, synchronization with duet/team members and/or to the music, and the level of difficulty, whereas the overall and artistic impression score rates the choreography, music interpretation, and the manner of presentation. In both cases, TCS is up to a maximum of 100 points (39).

Physiological responses in competitive events

Information available on the physiological stress during SS is very scarce and several authors have noted the methodological difficulties to assess physiological parameters during SS performance (12, 38, 101, 135). This is partly because of the challenges of taking measurements in the pool, especially when so much time, up to 50%, is spent underwater (56).

Most studies have attempted to address the physiological responses focusing on heart rate (HR) and blood lactate measurements during different types of SS training such as figure execution (47, 56, 57), routine elements (120, 134), and simulated competitive routines (12, 26, 64, 99). However, it is difficult to make any generalization about these results given the differences in the tests conducted and the methodologies. Moreover, the validity of this research for current synchronized swimmers may be further limited because the sport has since changed to become more athletic with the addition of acrobatic elements, increased speed of movement, a requirement for more power, and a greater level of complexity and difficulty in the routines. On the other hand, different from training, competition is a challenging situation which usually stimulates higher psycho-physiological responses in the participant (127). Unfortunately, barely any of these assessments have been performed during real competition, making it difficult to derive valid information on the physiological demands of the sport and its different events (64). Then, today's competitive demands need to be characterized during real competition, thus requiring a field study design, with some intrinsic limitations imposed by the competition rules on the one side, and by the aquatic environment on the other. This thesis is focused on further studying the physiological responses in modern competitive SS.

Cardiovascular response

A unique aspect of SS is the frequent and often lengthy breath holding (BH) periods while performing high-intensity exercise underwater. The combination of movements in the pool, with sequential or simultaneous jumps, strokes, acrobatics, and diving across the SS routines yields HR values proportional to exercise intensity (64, 99, 120) but also induces a HR decrease (bradycardic response) similar to diving alone (3) or combined with low intensity exercise (55). Thus, the HR pattern would vary depending on the exercise intensity, the swimmers' breathing pattern and the long term adaption to apnea training.

The diving response

The combination of physiological reflexes elicited by BH in humans and many other air-breathing animals is collectively called the diving response (33, 49). The characteristics of the classical human diving response are a reduction in HR or bradycardia (63), a decrease in cardiac output (80), a redistribution of blood flow due to peripheral vasoconstriction (52) and an increase in mean arterial blood pressure (37). The diving response is initiated when the head of the human is submerged.

The two principal sensory inputs have been described as facial neural activity and cessation of respiratory movements (32). The cessation of breathing *per se* leads to a reduction in stretch-receptor activity which initiates the diving response (33, 78). The effects of respiratory arrest and facial cold stimulation appear to be additive, where a combination of both causes the strongest diving response (10, 33, 60, 83, 112). Then, BH epochs responds not only to water immersion (IM), but also to face IM (111).

Bradycardia

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 (77). The bradycardia is mediated by the parasympathetic efferent pathway, where increased vagal activity causes a reduction in HR (78). It is an essential protective reaction of the cardiac system aimed at economically managing O_2 (9) whose magnitude is often used to estimate the overall magnitude of the diving response (33, 78). The economical use of O_2 results from lowered myocardial O_2 demands causing a decrease of the cardiac output (13).

After 25-30 s of apnea and cold stimulation, the bradycardia is fully established (78). During the first 10-15 s of underwater BH swimming in humans, the cardiovascular response (as indicated by HR) is similar to that seen during a similar level of exercise while breathing air. From then on there are a progressively more intense bradycardia which is indicative of an oxygen conserving response consisting of reduced perfusion of most of the body except the heart, central nervous system (CNS) and active locomotory muscles.

Several studies have been shown that facial cold stimulation without apnea causes a bradycardia similar in size as during apnea alone (33, 60, 83). It has been shown that chilling of the forehead results in a more pronounced bradycardia than that which is obtained when other facial areas of similar size are chilled (114). 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 (114). The potentiation of the diving response through stimulation of the cold receptors in the face depends on the difference between water temperature and ambient temperature (113). In this line, there is no difference in bradycardia between face IM apnea and whole body IM apnea (88).

The degree and rate of onset of this proposed O_2 conserving response are influenced by the intensity of the exercise performed while under water and whether or not the period of underwater BH swimming is preceded by exercise (23). Studies have been conducted on a host of bradycardia-modifying factors. For instance, hypoxia, the area of cold stimulation, lung volume, alterations of the intrathoracic pressure (Valsalva manoeuvres), high metabolic rate (high initial heart rate), level of physical activity, age, long and short term training, and psychological factors such as anxiety have influence on the magnitude of apneic bradycardia in humans (49, 54).

Exercise influences

In contrast to apnea at rest or under steady-state exercise, apneas initiated at the same time as the exercise put two different, conflicting stimuli on the human body simultaneously. One is the transition from eupnea to apnea, as in resting and steady-state exercise apneas, leading to increased parasympathetic activity at the heart, which decreases heart rate (49). The other one is the transition from rest to exercise, leading to parasympathetic withdrawal (41, 68) and increased sympathetic activity at the heart, which increases HR (61). Since apneic parasympathetic influence on HR does not change with different workloads, a stronger parasympathetic withdrawal and sympathetic input on the pacemaker of the heart, as achieved by higher exercise workloads, should attenuate and/or delay the diving bradycardia. Thus, while apnea and facial IM would increase the parasympathetic tone causing HR reduction (78, 112), exercise enhances the sympathetic stimulation of the heart (64) and increases HR.

Long term adaption to apnea

Decreases in HR during exercise and prolonged BH for trained subjects with breath hold diving experience have been reported in the literature (47, 55, 75). Particularly in SS, Alentejano *et al.* (2012) (2) reported higher HR values during exercise with apnea for non BH trained subjects compared to synchronized swimmers. In addition, it has been suggested that the degree of bradycardia tends to be high in synchronized swimmers who are skilled and experienced (47, 57). In this line, the greater HR decrease for the trained swimmers would support a greater adaptation to BH in the trained swimmers and this would likely translate into a conservation effect of O_2 (2). Then, it is plausible to think that their exaggerated diving response and superior apneic ability could be at least in part a product of their apnea training.

Anaerobic metabolism and performance

In SS, during the exercise bouts in apnea the challenge is to sustain exercise with the best technical execution during progressive systemic hypoxia. While in the competitive freediving disciplines the level of exertion is relatively low, in SS the athletes are exposed to hypoxia because the combination of BH and vigorous exercise (29). Actually, synchronized swimmers need to combine technically, physically, and esthetically very demanding routines (in the solo, duet or team events), lasting about 2 to 4 minutes (39) performed at increasingly higher levels of intensity with the 50% of this time spent underwater (56). Then, the sport seems to require high levels of aerobic and anaerobic endurance (134), as well as exceptional breath control when upside down underwater (64). Attending to the intermittent breath pattern of these athletes, characterized by frequent and intense bouts of dynamic apnea interspersed by short breaths, the La_{peak} concentration should be analyzed cautiously due to:

1) The specific influence of the BH periods. The function of the diving response is thought to be temporarily oxygen conserving which it potentially does in several different ways. The reduction in HR itself could reduce the O_2 requirements of the heart (78), while the peripheral vasoconstriction redistributes the blood flow, thus directing the O_2 mainly toward the most O_2 dependent organs, the brain and the heart (33, 37) and during exercise in apnea, also to the working muscles (23). Because the diving response is characterized by a peripheral vasoconstriction that reduces tissue blood flow, tissue O_2 consumption is also reduced, thereby causing a reduced depletion of both the venous and lung oxygen stores. Affected tissues are forced to derive energy from high-energy phosphates, from aerobic metabolism with tissue oxygen stores, and from anaerobic metabolism with lactic acid formation (8, 36, 37). In this line, the oxygen conserving effect of the diving response is further supported by measurements on blood lactate concentration. In fact, blood lactate concentration has been shown to increase from control after apnea (8, 37), with an even stronger increase after face IM apnea (8, 112).

Then, one could speculate that the more reduced peripheral O_2 delivery due to the longer or more frequent BH periods (14, 56), the higher the lactate production due to hypoxemia. Furthermore, according to the time spent underwater in international competitions—solo (62.2 %), duets (56.1 %), and teams (51.2 %) (56) it is plausible to think that the average values in blood lactate accumulation may vary depending on the event executed, which is a an important topic of one of the studies in this thesis (I).

2) The activation of the glycolytic metabolism in the exercising muscles. According to the “lactate shuttle” hypothesis (22) at the onset of exercise, blood lactate release from working muscles contributes to the elevation of circulating lactate concentration, but as exercise continues, working muscle consumes and oxidizes lactate on a net basis as production continues. Because skeletal muscle is capable of simultaneous lactate production and removal, it should be avoided interpreting the La_{peak} values in terms of the sole variations of its cellular production because lactate in blood samples reflects the balance between production and catabolism (mainly intracellular and in other organs and less active muscles) (66).

From a mechanistic perspective, lactic acidosis decreases the affinity of myoglobin and hemoglobin for O_2, thus facilitating O_2 diffusion to muscle mitochondria for sustained oxidative phosphorylation during the apneic bouts. However, in competitive freediving disciplines, systemic hypoxia may prevent this, leading to accumulation of lactate at an earlier state. In this case, the lactate removal from working muscles may be compromised by selective vasoconstriction. As a result, some peripheral regions may be excluded from perfusion, with the consequent reliance on anaerobic metabolism (35) and considerable regional differences in lactate concentration (110).

The specific training adaptations

The diving response has been found to be stronger in subjects trained in breath-hold diving compared to untrained subjects (111). Recent research comparing the physiological effects to BH at rest and during exercising between synchronized swimmers and controls, showed that the first exhibited an enhanced ability to breath hold with similar respiratory responses but a lower HR while BH and during recovery, suggesting a better adaptation to BH in both situations (2, 3). Several studies in SS have shown a reduction in hypercapnia sensitivity (14), an increase in tolerance to CO_2 (3, 38), and a decrease in their ventilatory response to any submaximal exercise (12) in this kind of athletes.

Although prolonged apnea causes hypoxemia which may lead to severe blood acidosis due to the association of hypercapnia and increased lactic acid concentration (79), there is some evidence that trained breath-hold divers exhibit reduced blood acidosis and oxidative stress compared to non-divers after both static and dynamic apnea as well as after non-apneic control exercise (67). This may be considered an adaptive mechanism to repeated apnea because both acidosis and oxidative stress have noxious consequences on cellular and organ functions. Then, trained swimmers may be more efficient, relying more on aerobic metabolic energy production and less on anaerobic glycolysis while BH in comparison to the BH controls (2). This is supported by a longitudinal study on four elite synchronized swimmers showing a decrease in total net lactate accumulation along a season of training (120), and by another study in which 5-week technical training program resulted in increased technical scores obtained in a team routine, but decreased performance and greater decrease in $\dot{V}O_{2}peak$ and La_{peak} in a 400-m swim (26). Training practice seems to produce such adaptations improving effectiveness at both peak and submaximal exercise (76) both in aerobic and anaerobic metabolism, which would explain the improvements in work economy.

Rating of perceived exertion

Perceived exertion refers to the subjective level of effort during exercise and results from the cognitive processing of information derived from multiple sources. Work related signals such as muscle strain and pulmonary ventilation, sensory signals derived from exercise environment, and cognitive strategies developed by individuals to cope with the stress of exercise are all integrated in central processing to generate a sense of effort or exertion (94). A RPE score 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 (106). Borg scales are based on subjective feelings of exertion and fatigue with the aim of both prescribing and regulating exercise intensity (16).

The inputs for RPE can be categorize into those of central and local origin (96). 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 (137). Meanwhile, local factors supply the primary perceptual input at low to moderate exercise intensities, while central factors dominate at higher intensities (96).

Previous investigations have proven that RPE scales are useful tools for quantifying exercise intensity based on their relationship with criterion physiological measures such as HR, blood lactate concentration, oxygen uptake and minute ventilation (27). Furthermore, there is some evidence that a very good prediction of subjective increase may be obtained by combining two simple variables from a work test, e.g., peak HR and blood lactate (18). However, it is well known that a significant portion of the variability in RPE is explained by non-physiologic factors (90).

Psychological and other factors

The RPE can also be influenced by psychological variables (17, 42, 118) such as mood or affect (30, 98), as well as by the time of day (34), exercise history (31, 98) and physiological condition (25), all of which may undermine the relationship between RPE scores and the physiological indicators of exercise intensity. In fact, Morgan (1973, 1994) (90, 91) suggested that approximately one-third of the total variance for RPE can be attributed to psychological input while the remaining two-thirds can be attributed to physiological factors.

Menstrual cycle influence

There are evidences that aspects of the physiological response to exercise, such as thermoregulation, ventilation, and cardiovascular strain, are influenced by hormonal fluctuations across the menstrual cycle (9–12). These fluctuations may also be associated with differences in psychological or subjective responses to physical activity (e.g., perceived exertion and pain) across the cycle (58). Little is known about the effects of hormonal fluctuations on the more subjective or psychological response to exercise specially among elite sportive women. Even though most research suggests that O_2 consumption, HR and RPE responses to submaximal steady-state exercise are not affected by the menstrual cycle, several studies report a higher cardiovascular strain during moderate exercise in the mid-luteal phase (65). For example, Pivarnik *et al.* (1992) (100) reported higher RPE values during the luteal compared to the midfollicular phase, when both progesterone and estrogen are high. Participants in another study had greater RPE during the ovulatory phase (days14–16) compared to the midfollicular (days 7–8) and midluteal (days 22–23), when only estradiol is high (109). In contrast, other studies have found no conclusive evidence for changes in RPE across the cycle (30, 31, 42, 65). The inconclusive findings could be a result of the use of small samples of highly active women (typically 8–10 women), which are limited in their power to detect psychological effects.

Fitness level

It is well known that during exercise athletes with a moderate fitness level perceive exercise to be relatively more strenuous and feel that they can continue for less time than highly fit 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 (46). The possibility of a category-effect on swimmers' RPE was addressed in Study I of this thesis.

Exercise with music

In SS, music plays an important role. The simultaneous stimulus of music and cognition of fatigue caused by exercise are both recognized as sensory information. Thus, listening to music appears to "relax" the cognition of fatigue due to exercise. Then, music could act as an effective passive distractor during exercise and would be associated with lower RPE (102). However, during the exercise at high intensity, the cognition of fatigue may be more predominant than that of music, which suggests that exercise intensity would exert a more powerful physiological effect than music (136).

RPE are known to be highly dependent on the size of the muscle groups involved (5, 19, 45, 55, 97, 118). Gamberale (1972) (45) and Pandolf *et al.* (1984) (97) both suggested that accuracy in perceiving the intensity of effort was increased when the activity was performed by a small group of muscles (the arms rather than legs).

Aquatic environment

In a study, Heithold and Glass (53) compared the RPE during the same aerobic exercises in and out of water. The duration was identical, being the velocity of performance of each exercise subjective. The results showed a tendency to lower RPE values in the water environment, especially during exercises exclusively with the lower limbs. In aquatic disciplines, subjective symptoms such as difficulty of breathing, heart pounding and exertion in the arms or legs while swimming seem to be different from those while physical work on land because breathing pattern, body position and use rate of the legs and arms are different for each exercise (70). Furthermore, the water temperature of the pool could affect the perception of effort as lower RPE values have been reported during exercise in cold conditions compared to warmer conditions (51, 125). On the other hand, during field exercise on an outdoor track, RPE values have been reported significantly different from those obtained during laboratory testing (25) which indicate the limited usefulness of assessing the RPE based on laboratory determinations (103). In this context, the environmental conditions seem to play a role in the way athletes perceive exertion (103).

Internal training load

Importance of monitoring the internal load

Physical training is the systematic repetition of physical exercises, and it can be described in terms of its outcome (anatomical, physiological, biochemical, and functional adaptations) or its process, that is, the training load (the product of volume and intensity of training) (126). In elite SS, current training demands often result in high-volume (averaging about 40 h·week^{-1}) (93, 107), high-intensity training programs (93), including long periods devoted to choreography when much time is spent in the pool to perfect synchronization. Then, regulation of exercise intensity during training is critical to the success of each conditioning program since exercise intensity set too low does not induce the desired physiological adaptations while an exercise intensity set too high may result in overtraining fatigue or injuries for overuse in this kind of athletes (28, 92, 93, 131). In this line, balancing the training components to produce the desired result at competition time without producing overuse injuries should be the major task for all SS coaches (93). To achieve this goal, it is critical to monitor and control the training process, with a valid measure of the swimmers' training load.

There are a variety of monitoring methods used by coaches to measure the physical load undertaken by athletes during training. However, in sports such as SS, few valid and reliable methods are available to evaluate the training load. Typically, the majority of training programs are prescribed using a measure of external load, which is defined as the work completed by an athlete measured independently of his or her internal characteristics. For example, in SS, coaches often prescribe training with reference to external measures (e.g., number and duration of sessions, type and number of elements, sets and repetitions, etc.) despite the fact that the same external load can elicit different physiological responses and training adaptations depending on the swimmer's age, fitness and skill level (15). Thus, although the training process is often described in terms of the external load prescribed by the coach, the internal load is a key component of the training process in order to set the optimal dose-response relationship between training stress and adaptation (126). This is particularly relevant in this kind of aesthetic sports, in which the planned external load is often different for each team member because of the variety of elements configuring each routine and the order in which they are executed.

Methods for controlling the internal load

Currently, the most widely used method for evaluating the internal load during training consists of using HR as a measure of exercise intensity. However, the routine use of HR-based methods is not spread due to the time-consuming process of collecting HR data of all swimmers during every session, the cost of numerous HR telemetric systems, and the fact that using HR transmitter belts is not permitted during official competitions. In addition, HR monitoring devices often incur in technical failure in water, and manual pulse palpitation requires interrupting the exercise (104). Additionally, the HR response can be a poor method for evaluating intensity during high-intensity exercise such as weight, interval, intermittent, and plyometric training (40).

An alternative strategy to quantify the internal load is the RPE method. The Borg CR-10 scale developed by Borg *et al.* (1982) (16) is a category-ratio (CR) scale anchored at numbers 1 to 10, the later representing extreme intensities. Previous studies had pointed out high reliability and validity coefficients between physiological variables and RPE using the CR-10 scale (85, 86, 89, 117). Moreover, some characteristics of this scale, such as its noninvasive, easy administration in field contexts and lack of requirements of specialized staff, may favor its use to indicate the intensity avoiding the expensive use of HR monitors. Based on the findings that SS requires high levels of aerobic and anaerobic endurance (64, 107), the Category-Ratio (CR-10) Scale (17) appears to be one of the best choices, not only regarding its psychometric characteristics and criterion-related validity (27) but also for being especially useful in measuring anaerobic efforts (95).

Previous investigations have proven that RPE using the CR-10 scale can be used to assess the internal load imposed by exercise both during training (85, 86, 89) and competition (21, 89, 117). Additionally, a number of studies have supported the validity, reliability and the practical application of the RPE scales to quantify exercise training intensity in aquatic disciplines such as competitive swimming (50, 104, 128), acrobatic diving (85), and recently in SS (124). Tan & Long (2010) found in five synchronized swimmers that post-training salivary cortisol levels correlated with RPE ($r = 0.64$, $P < 0.005$), which seems a sensible approach considering the use of RPE for controlling the internal load in SS (124).

The specific influence of competition

Different from training, competition is a challenging situation which usually stimulates higher psycho-physiological responses in the participant (127). Research in this field suggests that the stress due to competition is added to the physiological stress caused by exertion, which in itself is capable of affecting hormones secretion (62, 127) and autonomic nervous system activity (24) producing changes in many cardiovascular parameters (e.g. increasing HR) (20, 87). Semin *et al.* (2008) (116) and Viru *et al.* (2009) (127) observed that endurance trained athletes attained similar mean HR responses between training and competitive sessions. In contrast, several investigations on taekwondo practitioners (20), basketball players (87) and long distance runners (115) found that mean HR was higher in competition than during training.

In addition, competitive performance is more affected by decision-making and psychological aspects, since there are opponents and the result is of greater importance. Prior mental fatigue and anxiety induced by a challenging competitive event could elevate the RPE throughout exercise and hastens exhaustion (69, 82). By contrast, motivation, higher degree of self-efficacy or the willingness to exert effort may counteract any negative influence of higher RPE (69, 132).

In a practical sport setting, the use of markers that precisely reflect the magnitude of the stress related to different conditions and environments could help coaches to better understand how the athletes are coping with stressors, thus providing valuable information to optimize training. Attending the demands of the training schedule in elite SS, comparing the internal load by means of RPE (perceptual marker) and HR (physiological marker) responses during both specific training and competition seems adequate to ascertain whether swimmers may achieve the competitive intensity during training sessions, which is the topic of one of the studies in this thesis (II).

Effect of immersion on perceived exertion

In our first Study (I), a group of elite synchronized swimmers was shown to exhibit differences in RPE values during various competitive routines. Team events, both in technical and free program elicited lower RPE scores compared to solos and duets (*P* < 0.005) (Figure 3) (107). It is well known that the time spent underwater in international competitions varies among events—solo (62.2 %), duets (56.1 %), and teams (51.2 %) (56)—which suggest a possible relationship between the time spent underwater and the perceived exertion. On the other hand, RPE in elite SS appears not to be influenced by the competitive stress (108). Ten Olympic SS medalists performed the same competitive TD or FD in a training session and during an official competition showing non-significant differences (5%, *P* > 0.05) in RPE scores between both sessions (II). These results suggest that the time spend underwater during the routines would be associated with or even triggers an increased perceived of exertion in SS, independently from competitive stress.

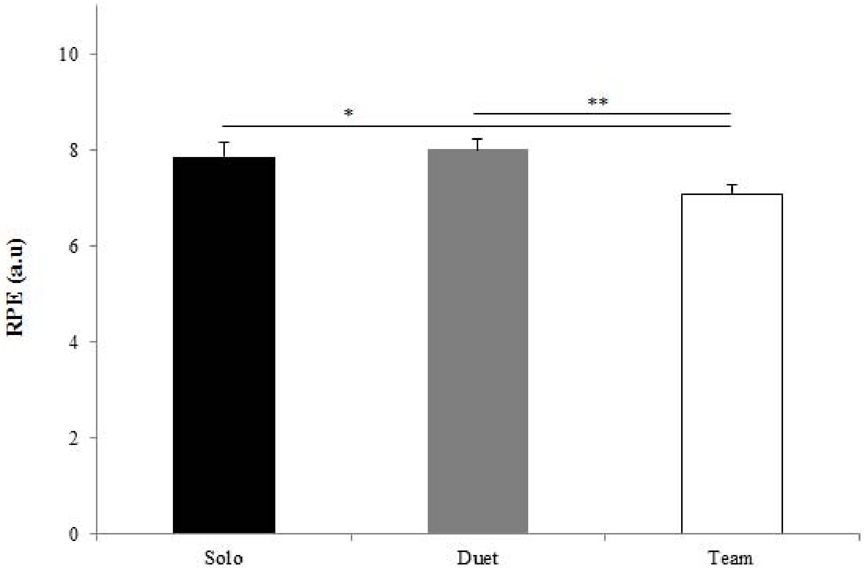


Figure 2. Average changes in RPE of elite synchronized swimmers (n= 34) in the events of the competitive program. Differences among events are depicted by * P < 0.05 and ** for P < 0.005. (107)

For the above-cited studies RPE and physiological correlates were analyzed. The moderate relationship between La_{peak} and RPE (107), the inverse relationship between RPE and minimum HR, and the absence of association with peak HR (108) support the concept that the duration and/or frequency of bradycardic events may play a more important physiological mediator for RPE than lactate (108).

Under hypoxic conditions, it has been shown that the peak HR is not significantly related to either the overall or the peripheral muscular RPE after allowance for the other variables, while the respiratory minute volume and the relative maximal O_2 intake become more important determinants of effort perceptions under these conditions (118). In this line, a recent review showed that respiration rate is among the best indicators of physical exertion (27). Thus, given the nature of the routines in which swimmers tend to spend 50% of the routine underwater (56), it seems plausible to think that the perceptions primarily associated with the cardiorespiratory system resulting from tachycardia, tachypnea, and dyspnea (137) may provide a relatively greater input for the synchronized swimmers' perceived exertion than peripheral effort perceptions (i.e. for arms and legs) (108). Swimmers under greater physiological strain—and consequently added psychological input—would be capable of discriminating this information and exhibit specific physiological responses (125). The use of RPE as a holistic assessment tool for monitoring the internal load in SS was evaluated in Study III of this thesis.

Hypoxia related to perceived exertion

There has been very little previous research on the effects of hypoxia on perceived exertion. Lower levels of RPE have been found during hypoxia using real (59) or simulated (4) altitude, as well as low oxygen mixtures (48). Reduction of O_2 could change RPE by 1) dulling cerebral perceptions, 2) stimulating hyperventilation, 3) shortening task duration, 4) reducing muscle tension at a given fraction of inspirate-specific peak O_2 intake, and 5) increasing the local accumulation of hypoxic metabolites for a given power output (118). Shephard *et al.* (1992) (118) pointed at a distorting influence of hypoxia if respiratory sensations are used to “fine-tune” an exercise prescription. In their study, subjects, all of whom capable of distinguishing effort ratings for three types of sensation (overall, respiratory and peripheral muscular), decreased both general and respiratory sensations after performing exercise in hypoxia as compared to normoxia (118). Accordingly, such variations of perceptions would limit the possibility of using respiratory sensations as a means of regulating the relative intensity of exercise (118). However, it is known that the overall average RPE apparently offers a better basis for exercise prescription and intensity control than muscular or respiratory perception of effort (118). Thus, it has been proposed that the intensity of prescribed exercise and its control should be “fine-tuned” by the individual, based upon the conjunctive use of personally monitored perceptions, either overall perceptions of exertion (105) or breathlessness (11).

Besides the studies considering the relationship between hypoxia and RPE, the only other study that particularly referring to changes in RPE with regard to hypoxia in competitive sport is one that briefly mentions lower RPE values in 11 male competitive middle- and long-distance runners after 1h treadmill running in hypoxia as compared with normoxia (43). Hence, these results would suggest a possible “apneic” effect on perceived exertion in SS as a result of the frequent immersions, which was the main focus of Study III.

OBJECTIVES AND AIMS

The general objective of this investigation was to characterize the cardiovascular, blood lactate and perceived of exertion responses during the execution of different competitive routines in elite SS, with specific focus on the effect of intense exercise in apnea. This general objective can be divided into the following aims, which are addressed in specific papers (in roman numbers):

(I) Physiological responses in relation to performance during competition in elite synchronized swimmers:

1) To describe the cardiovascular, lactate and perceived exertion responses in junior and senior elite synchronized swimmers during an official competition both in technical and free programs.
2) To relate these physiological parameters with competitive performance.

(II) Monitoring internal load parameters during competitive synchronized swimming duet routines in elite athletes:

1) To investigate and compare the internal load imposed by duet routines performed during training and competition by means of heart rate monitoring and perceived exertion assessment in elite synchronized swimmers.
2) To determine whether there is a relationship between both types of assessment in each of these conditions.

(III) Perceived exertion, time of immersion, and physiological correlates in synchronized swimming:

1) To evaluate whether the rating of perceived exertion is an appropriate tool to assess the internal load in competitive synchronized swimming by determining the relationships between perceived exertion scores and the physiological response during the most demanding competitive events (solo and duet).

2) To verify whether there is a relationship between body immersion parameters and the rate of perceived exertion.
3) To determine which of these parameters can explain the perceived exertion in competitive events.

METHODS

Subjects

In total, 34 high-level female synchronized swimmers, including all swimmers in the Spanish National junior and senior teams—among them Olympic (n=10), absolute (n=4) and junior (n=7) World Championships medalists—volunteered for these studies. They all had competed at national and/or international level at least in the previous two years. 24 were juniors (15-18 years) and 10 were seniors (>18 years). Their physical characteristics are presented in Table 1.

Table 1. Physical characteristics of subjects

	All swimmers (n=34)	Junior (n=24)	Senior (n=10)
Height (cm)	165.2 ± 6.5	163.7 ± 5.1	168.9 ± 8.0
Body mass (kg)	53. 6 ± 5.6	53.2 ± 5.3	54.6 ± 6.3
Age (years)	17.5 ± 3.3	15.9 ± 1.0	21.4 ± 3.6
Training ($h·week^{-1}$)	33.1 ± 10.0	29.9 ± 8.2	40.7 ± 10.1
Years of practice (years)	9.6 ± 2.5	8.7 ± 1.5	11.7 ± 3.3

The sample of Study I was composed by the entire group of swimmers. The participating subjects in Study II were limited to those that competed at international level and participated in the duet event at the Spanish Synchronized Swimming National Championships 2011. The sample was composed by 10 elite swimmers, 7 juniors and 3 seniors. All of them were medalists in the London 2012 Summer Olympic Games during the season of the study, 8 in the free team and 2 also in the free duet. A group of 17 elite 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 Study III. They were selected from the entire group of swimmers in

Study I and were those who competed on the technical, free solo and/or duet event. More information on specific swimmers' characteristics can be found in the respective papers (II and III).

Procedures

Data collection took place during the third microcycle of the competitive period. These studies were performed the week before (Study II) and during the 2011 Spanish Synchronized Swimming National Championships (Studies I-III). All routines were performed during the actual competition (n=96) and had the approval of the Refereeing and Organizing Committees of the Royal Spanish Swimming Federation.

Prior to and at the start of the competitive and training sessions all volunteer swimmers and their coaches were informed about the scope and methods of the study and delivered a written informed consent, with parental permission when needed. The studies were conducted in conformation with the principles of the Declaration of Helsinki and had been approved by the Ethics Committee for Clinical Sport Research of Catalonia.

To limit the influence of diet on the variables analyzed, especially blood lactate concentration, all athletes were instructed to ingest similar nutrients before the competition (Studies I and III) and the training session (Study II) and were allowed to drink water *ad libitum* before each testing session. Because both ambient and water temperature may influence diving bradycardia in humans and the overall HR response (113), all the routines took place at similar water (25–26ºC) and air temperature (26–27ºC) in a 50-m indoor pool. Due to restrictions imposed by the official rules and for ecological validity reasons, we were constrained to monitoring HR, post exercise blood lactate concentration and RPE during the competitive routines.

Competitive session

Prior to competition (Studies I-III), all swimmers performed 45-60 minutes of general warm-up including swimming, figures, and monitored routine exercises without music. Additionally, 30 min before their performance all swimmers were allotted 20 min of specific rehearsal with music, generally involving the execution of the whole routine and selected parts. In all three studies HR monitors were placed before the warm up and not removed before 15 min after the routine was executed. Capillary blood samples were taken after warm-up and immediately before the call to perform, and 3, 5, 7, and 10 min after each routine (Studies I and III). The Borg CR-10 category-ratio scale was shown to the swimmers immediately after completing the routine (Studies I-III). Every competitive routine was assessed and marked by the official judges of the competition according to FINA rules (39) and continuously recorded using a digital video camera. In studies I and III most swimmers performed in more than one event, and thus were included in more than one routine group.

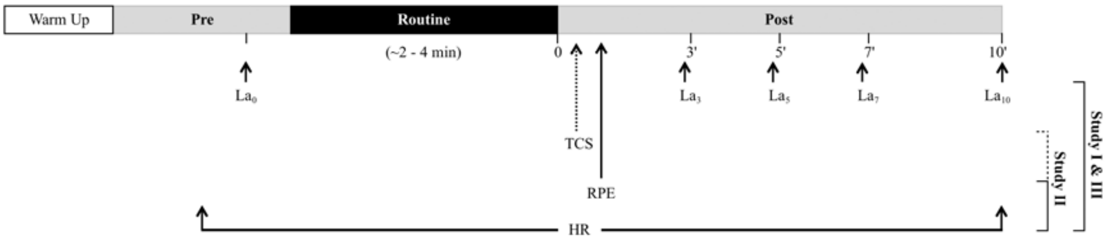


Figure 3. Study protocol in studies I, II and III

Training session

In Study II, after a 30-min standardized warm-up including swimming, figures, and monitored routine exercises followed by a full passive recovery period, the swimmers completed the same competitive TD or FD routine with the same partner as in the approaching championships. Swimmers were informed of the aim of the study and were encouraged to perform at their best. The training session was separated by 48 to 72 h the week before. In this case, both routines (training and competition) were executed in the morning at about the same time of day (± 2 h), and allegedly at similar points in their ovarian cycles to minimize the difference caused by the biological rhythms effect (129) and changes in performance ability.

Figure 4. Spanish Olympic duet performing the free program in both situations, during a competitive and a training session

Testing effect

The week before competition, all participants were given specific instructions on the meaning and use of the RPE scale, and were assessed repeatedly during at least three training sessions so as to disclose learning effects (104) and to improve the consistency of the measurements. In addition, to minimize potential instrumentation bias, swimmers wore the HR monitor during these previous training sessions. The recordings for monitoring the internal load of the training session (II) were carried out the last day of that week.

Parameters and equipment

For the recording of the cardiovascular and ratings of perceived exertion responses, non-invasive methods were used to monitor HR, RPE, blood lactate, and performance.

Heart rate

HR was measured continuously using waterproof monitors (CardioSwim, Freelap, Fleurier, Switzerland) which record beat-by-beat R-R intervals and lap times using transmitters' signaling. The belt contains two chest electrodes wired to a monitoring device that can be unloaded on a computer after the recording. Portable beacon transmitters (TX H2O, Freelap, Fleurier, Switzerland) were placed by the pool at different locations so that the monitors' microprocessor units could recall specific positions during the competition and training session. 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.

Figure 5. Synchronized swimmers wearing the waterproof HR monitors on the platform.

Ratings of perceived exertion

For the assessment of the RPE, the Borg CR-10 category-ratio scale was selected to rate the perceived intensity of exertion (17). A graphical, colored, verbal-anchored scale was shown to the swimmers after completing the routine during blood sampling. As mentioned above, it reminds unclear whether RPE for a given workload could be influenced by the menstrual cycle. For that reason, we attempted to control for these variables by testing the swimmers at the same time of day and under similar temperatures (pool water temperature ~25ºC), and avoided testing them from 72 hours before menstruation and during the luteal phase.

Blood lactate

At every competitive session (I and III), following warm-up and a 5-min recovery period and before the call to perform, 10 µL of capillary blood were drawn from the ear lobe. Samples were also taken 3, 5, 7 and 10 min after the routine. Blood samples were immediately analyzed using a lactate photometer (Diaglobal DP100, Berlin, Germany) which had been previously calibrated using lactate standards obtained by dilution (2, 4, 8, 10, 12, 16, and 20 mmol·L^{-1}). The highest value was taken as the peak post-exercise lactate concentration (La_{peak}).

Figure 6. Capillary blood sampling

Video recording

Each routine was video recorded using a digital video camera (Panasonic AG-DVX100BE 3-CCD Mini-DV Cinema Camcorder) at 625-line/50Hz PAL interlaced video mode. The stationary video camera was placed at an elevated site by the pool, located 1 meter away from the edge, just in front of the judges’ podium, and perpendicular to the midpoint of the 30 m area available for competition. The professionally operated camera recorded all swimmers’ 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.

Analysis

Data Analysis

Absolute values of the HR, lactate and RPE responses were analyzed for each age category (junior *vs.* senior). In addition, the differences between training and competition routines for each HR and RPE parameter were determined (II). Some IM parameters during the solo and duet events both in technical and free programs were registered for analysis (III). For more details on the physiological and IM variables see the respective papers. Data recording and analysis was done on computers with the help of data acquisition software (CardioSwim, Freelap, Fleurier, Switzerland). For identifying and timing IM phases, images were decoded and registered with specific free software (LINCE, version 1.1, Barcelona, Spain) (44). Spreadsheet software (Excel, Microsoft, USA), signal processing software which included interpolation functions and smoothed (MATLAB® version 7.10.0. Natick, Massachusetts: The MathWorks Inc., 2010) and statistics software (PASW for Windows, version 18.0 (SPSS Inc., Chicago) were used data processing.

Statistical analysis

Statistical comparisons consisted of a mixed multiple ANOVA for fixed effects and interactions (I and III), and a paired *t*-test after Shapiro-Wilks test for normality (II). ANOVA with Bonferroni correction was used for multiple comparisons when necessary (I and III). Pearson’s correlation coefficients and stepwise multiple regression (P_{in}= 0.05, P_{out}= 0.10) with TSC and RPE as dependent variables and all physiological parameters as predictor variables were used in studies I and III. In all studies statistical significance was accepted at $P < 0.05$.

RESULTS AND DISCUSSION

Physiological responses in relation to performance during competition in elite synchronized swimmers (I)

Characterizing the physiological response

HR response

Cardiovascular demands of all SS competitive routines (Figure 7) can be best described as very high, regardless of their duration and technical content. A very intense anticipatory HR pre-activation was observed in all swimmers, even more pronounced in juniors. During the execution of all routines, cardiovascular demands were equally high in both age categories, with HR quickly approaching maximal levels, and interspersed periods of marked bradycardia during the intense exercise bouts performed in apnea.

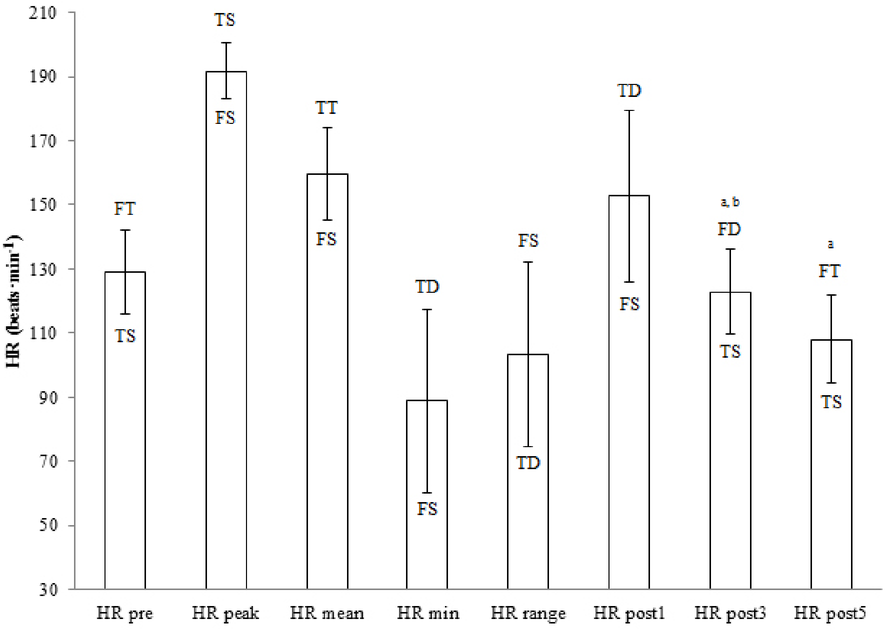


Figure 7. Heart rate (HR) parameters before (pre), during (peak, mean, minimum, range), and after (post 1, 3, and 5 min) competitive routines for the entire group of swimmers (n=34). Significant differences ($P < 0.05$) among routines were noted only during recovery [a]FT *vs.* TS; [b]FT *vs.* TD

During SS, the diving response appears to be powerful enough to override the HR response to exercise during apnea. Cardiac output is expected to be reduced throughout dynamic apneas, largely due to bradycardia, whereas the systemic vascular resistance would increase (6). These cardiovascular responses are obviously interplaying during water IM and BH phases due to intense exercise combined with BH, which would produce a rapid development of hypercapnia and hypoxia (55). While apnea and facial IM increase the parasympathetic tone causing HR reduction (79, 112), exercise increases sympathetic stimulation of the heart (64) and increases HR. Thus, when the swimmer starts holding breath during the routines, both inputs compete with each other for control of HR (130).

The observed periods of bradycardia in our swimmers, who reached minimum HR values of 75-95 beats·min^{-1} on average (mean 46% HR reduction) were similar to those found during dynamic apnea diving (7, 55, 130) and in SS during training exercises (14, 57, 64, 99), and was more pronounced than the 38% relative HR reduction observed during face IM during low-intensity (80 and 100 W) cycling exercise (6, 8). The combination of movements in the pool, with sequential or simultaneous jumps, strokes, acrobatics, and diving across the SS routines, yields HR values proportional to exercise intensity but also induces a bradycardic response similar to diving alone (3) or combined with low intensity exercise (55).

In all routines, high HR_{peak} values indicated a very intense activation of the cardiovascular system to ensure the high-energy turnover in the exercising muscles. During competition, HR rapidly increases showing an underlying pattern of exponential increase to asymptotic maximal levels with marked bradycardic episodes (see Figure 2, Study I). This suggests that BH oxygen conservation mechanisms would not fully prevent the activation of the cardiorespiratory system to provide energy for the exercising muscles despite blunting the HR response during the periods of apnea.

The fact that HR_{peak} was not different in juniors and seniors is likely to be an indication that all routines were performed at maximal intensity by all swimmers despite the observed differences in performance as quantified by final competition scores.

With respect to HR recovery parameters (HR_{post3} and HR_{post5}), the FT routines show a slower off kinetics then TS. We can only propose a plausible explanation to this observation, which is the lower average cardiorespiratory fitness in team swimmers as compared to soloists (all of them World medalists in our sample). This would be in accordance with previous findings showing that a lower HR during recovery is a specific adaptation in trained synchronized swimmers (3). Likewise, since both category groups exhibited similar HR off-dynamics, junior and senior swimmers in this study seemed to be similarly adapted to SS training. Whether this adaptation derived from similar levels of general cardiorespiratory fitness or to an enhanced ability to breath hold as a specific feature of SS training adaptation (3) could not be elucidated.

Blood lactate

This study shows a moderate post-routine blood lactate concentration (ranging from ~5 to 13 $mmol\cdot L^{-1}$ with an overall average of 7.3 $mmol\cdot L^{-1}$) in elite senior and junior synchronized swimmers (Figure 9), likely deriving from the large number of figures at high execution rate (101) and intervals of reduced peripheral O_2 delivery due to BH periods and the subsequent diving response (14, 56).

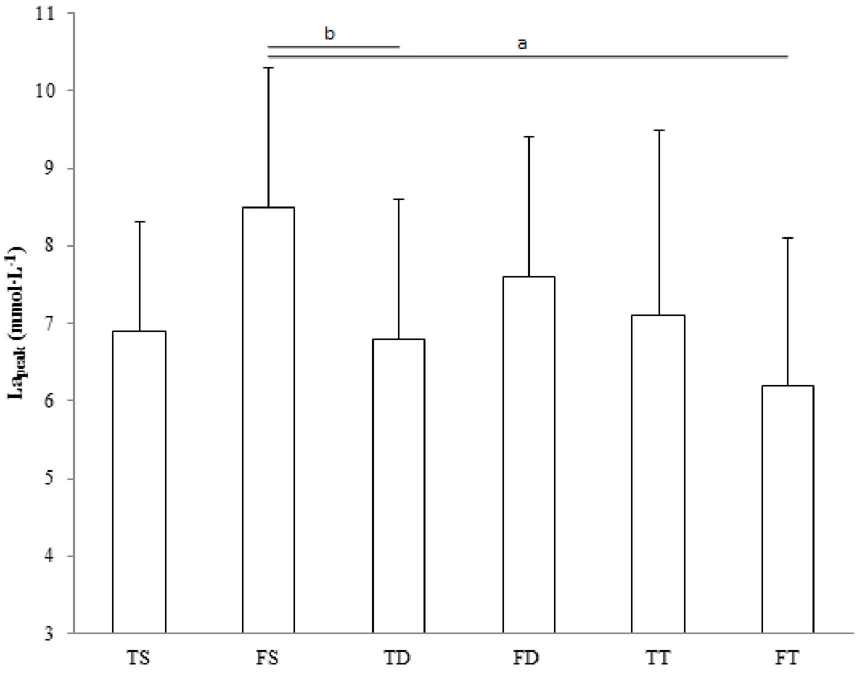


Figure 8. Peak blood lactate (La_{peak}) after competitive routines for the entire group of swimmers (n=34). Significant differences ($P < 0.05$) among routines were noted ^{a}FT *vs.* FD and FS; ^{b}FS *vs.* TD

According to the "shuttle hypothesis" (22) and due to the specific breathing pattern during SS—alternating intervals of dynamic and , the progressive lactate accumulation during the SS routines, increased O_2 supply may be made available, leading to prolongation of oxidative metabolism in parallel with anaerobic glycolysis (110). This would explain the differences in our data and those attained by free divers (110) and the similarities with underwater hockey players (8.0 mmol·L^{-1}) (75), whose breath pattern is similar than those of SS.

The highest La_{peak} values were obtained in FS and FD (Figure 8) suggesting a more intense activation of anaerobic glycolysis in solos and duets caused by their higher intensity and longer duration (~3-3.5 min) (134). Several hypotheses can be advanced to explain these results. On the one hand, free programs usually start with an underwater sequence which may last in excess of 45 s in the case of more highly placed contestants (29). In spite of blood flow redistribution, O_2 stores might be reduced at the onset of the routine and, hence, the working muscles would receive less O_2 than required due to peripheral vasoconstriction and would then rely more on glycolytic metabolism. On the other hand, the rate of execution of skill elements tends to be different according to the event (56, 57) then not being surprising that the choreographies composed by more figure parts (solos and duets) could imply a higher physiological stress with the concomitant increase in the net blood lactate accumulation. Although not analyzed in this series of studies, FS and FD routines may have involved harder elements and figures at the start of the routine with the concomitant increase in the workload, which would result in higher lactate formation.

In line with other studies (12, 101), we found no differences in La_{peak} values between junior and senior swimmers despite the higher training volume achieved by the seniors. On the one hand, since all swimmers were participating in an absolute championship and judged under the same rules, both age groups had to perform similar technical elements in a similar time pattern (39). On the other hand, the development of an adaptive metabolic adaptation may already be present in younger swimmers, already exposed to remarkably high training volume and intensity.

RPE

Mean RPE scores ranged from 6.6 (TT) to 8.1 (FD), with quite large inter-individual range of variation. RPE scores were significantly higher in juniors than in seniors (Figure 9), hence indicating that seniors perceived their performance to be less strenuous. The fact that all the swimmers (both age-categories) execute the routines under the same conditions (i. e music, exercise duration, water temperature, similar menstrual cycle phase) may explain that possible differences in RPE values if any can thus not be attributed to those parameters but also be possibly experience-related (46).

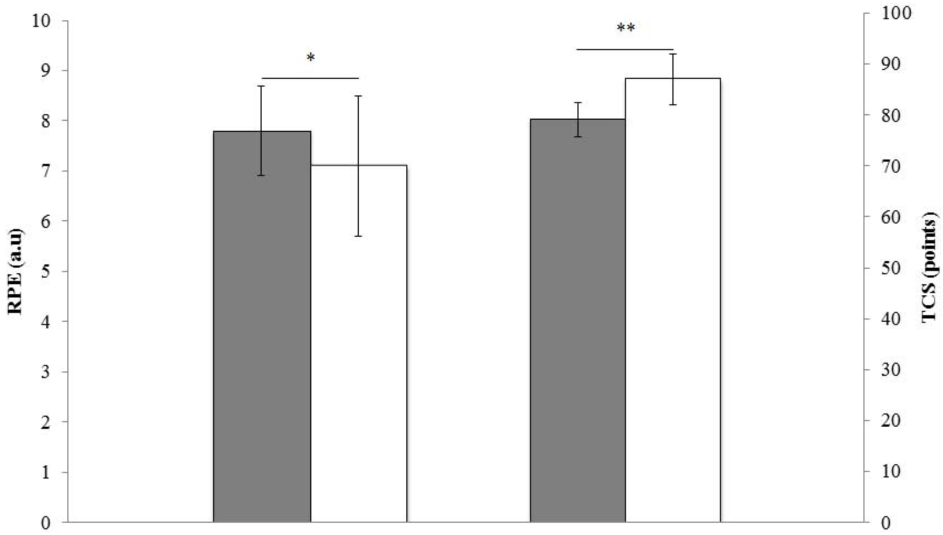


Figure 9. Average RPE (a.u) and TCS (points) after the competitive routines in ■ junior (n=24) and □ senior (n=10) elite synchronized swimmers. Differences between age-categories are depicted by *for $P < 0.05$ and **for $P < 0.001$

Predicting competitive performance

HR_{pre} and HR_{min} explained 26% of variability in performance (TCS), supporting the concept that an augmented diving response is associated to superior performance in SS. Even if this was an absolute competition, seniors (87.0 ± 5 points) were rated higher than juniors (79.1 ± 3.4 points) as expected (Figure 9). In relation to HR parameters, seniors showed a 11.7% decrease in HR_{pre} and 6% in HR_{min} than juniors. In Study I, the relationship between HR parameters and performance suggests that a higher skill level was associated with a lower anticipatory HR activation and lower levels of bradycardia, with subsequent higher HR range of variation. These relationships are consistent with the notion that the attainment of a proficient level of expertise is related to an improvement of motor automaticity and reduced attentional demands (1, 133), and also to specific physiological responses to apnea training, as suggested by previous studies (74, 75).

Lower anticipatory HR activation, has been associated to performance improvements in self-paced sport activities such as rifle and pistol shooting, archery and golf. The observed negative correlation between HR_{pre} and performance would reflect decreased afferent inputs to the brain and would result in more effective external focusing of attention and superior performance (71, 72). In addition, an elevated metabolic rate would further reduce the limited O_2 stores during apnea. The anticipatory HR response would increase the cardiac output before starting the exercise, with the concomitant increase in the rate of O_2 depletion limiting aerobic performance.

On the other hand, a more pronounced bradycardic response in the more experienced swimmers—and hence lower HR_{min} and higher HR_{range}—may be related to more prolonged BH periods in higher rated routine exercises or to a sharper decrease in HR as a consequence of the increased O_2 conservation effect in the more experienced swimmers (3). The results of the present study suggest show that an augmented diving response is beneficial for SS performance, however it clearly requires further investigation (see Study III).

Monitoring internal load parameters during competitive synchronized swimming duet routines in elite athletes (II)

Overall, the internal load imposed by duet routines assessed by means of objective (HR) and subjective (RPE) markers and the pattern of interaction between both indicators, were virtually the same during a real competitive situation and during training in this group of elite synchronized swimmers.

Comparing the internal load during training and competition

Table 2 shows the relative percent differences in HR parameters and RPE during the execution of equal routines during competition and training.

Table 2. Average relative changes (%) in HR parameters and RPE (n=10) during equal duet program execution at training (T) and competitive (C) session.

	HR_{pre}	HR_{mean}	HR_{peak}	HR_{min}	HR_{post1}	HR_{post3}	HR_{post5}	RPE
Difference T - C	2.32%	0.37%	0%	0.27%	2.27%	2.85%	1.14%	5.06%

The absence of differences between training and competition in the anticipatory HR pre-activation rates could be explained by automaticity. This suggests non-conscious attention to the act itself while in execution, and unaware of and therefore vulnerability to external and internal distractors (119). Although stress has been found to have a detrimental effect on performance disrupting automaticity (84), our results suggest that elite synchronized swimmers are able to self-regulate competitive anxiety, possibly through regulating expectations, confidence, and attention prior to and/or during performance (119). Thus, it seems reasonable to hypothesize that the attainment of a higher skill level—typically in elite swimmers—would be associated with a greater automaticity in performing motor acts and a lower metabolic energy cost for achieving the task goal, with the consequent reduction of attentional demands and favoring the use of an energy-efficient preferred mode (73, 119, 121), which in turn would imply a similar HR pre-activation response in both conditions.

The similarity in HR parameters during the execution in both experimental situations can be analyzed in terms of: 1) the specific influence of the diving response during BH periods due to the close correspondence in the time and duration frame of the frequent and often long BH periods in both conditions, 2) the lack of uncertainty in both conditions because of SS rules and the automaticity of the actions because of practice, all of which suggests non-conscious attention to the act itself while executing and unawareness of and vulnerability to external and internal distractors (119), and 3) the specific training adaptations. Continuous practice during training reduces the metabolic energy cost of performance while practice-related refinements to coordination and control are also associated with significant reductions in muscle activation (73) and HR (122).

Relationship between heart rate and perceived exertion

Based on recent research (89), we hypothesized that the pattern of interaction between the physical load (as reflected by the HR response) and the perception of effort during competition would vary due to the stress of competition. This study showed that RPE scores were inversely related to the minimum and mean HR levels, and positively related to the range of HR variation during exercise, whereas they did not relate to the peak or recovery HR. This strongly suggests a positive relationship between the perceived intensity of exertion and the duration and frequency of bradycardic events during the routines. In this line, the perceptions primarily associated with the cardiorespiratory system resulting from tachycardia, tachypnea, and dyspnea (137) might have provided more powerful stimuli for perceived effort changes than peripheral effort perceptions (i.e. for arms and legs), given the nature of the routines in which swimmers tend to spend 50% of the routine underwater (56). Moreover, the cardiovascular responses to apnea during dynamic exercise occur also during the recovery period (55), which would explain the decrease in swimmers' perceived exertion, leading them to give lower scores.

On the other hand, the moderate correlations reported would not support this method as a valid substitute of HR-based monitoring. It should be taken into account how different factors (e.g. exercise intensity, apnea, and autonomous neural control) contribute to perceived exertion in SS performance (see Study III). Thus, this simple method has the potential to become a valuable tool for coaches, but practice is necessary to get valid information from this internal load quantification strategy.

Perceived exertion, time of immersion, and physiological correlates in synchronized swimming (III)

This study revealed a significant association between RPE scores and the frequency and duration of immersions, the magnitude of subsequent bradycardic events, post-exercise blood lactate, and HR recovery during competitive SS routines.

Table 3. Physiological and immersion parameters correlates of RPE during competitive SS routines

	R	P-value
La_{peak} (mmol·L^{-1})	0.50^{**}	0.003
Heart Rate Parameters (beats·min^{-1})		
HR_{pre}	0.37^{*}	0.023
HR_{min}	-0.53^{**}	0.001
HR_{mean}	-0.38^{*}	0.019
HR_{peak}	-0.26	0.087
HR_{range}	0.45^{**}	0.006
HR_{post1}	0.07	0.360
HR_{post3}	0.44^{**}	0.008
HR_{post5}	0.45^{**}	0.006
IM Parameters		
NIM (times)	0.33^{*}	0.036
TIM (s)	0.58^{**}	<0.001
MIM (s)	0.30	0.438
RIM% (% of routine duration)	0.31^{*}	0.046
IMmax (s)	0.30	0.055
NIM>10s (times)	0.50^{**}	0.003
TIM>10s (s)	0.61^{**}	<0.001

R, linear Pearson's correlation coefficient; Significant linear correlation $^{*}P < 0.05$, $^{**}P < 0.01$ with RPE

Given the results of the study (Table 1), it seems reasonable to assume that the long and frequent IM and their impact on HR as a result of the diving response strongly influenced the perception of effort. This would be further supported by the strong positive correlation found between RPE and HR_{range}, which indicates the range of HR variation between maximum (i.e., exercise induced) and minimum (i.e., strongest diving reflex bradycardia). The lack of a significant (or perhaps negative) relationship of RPE with maximum HR might indirectly indicate that bradycardia has a greater influence on the perception of effort than tachycardia in SS exercise. Metabolic fatigue seems to also play an important role in the perceived exertion in SS, as reflected in the moderate relationship with post-exercise $La_{peak.}$

Association between immersion periods and RPE

With respect to the influence of immersion intervals 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. The hypothesis that prolonged and frequent immersions would result in increased RPE and that the central factors would elicit higher RPE values (II and III) is supported by the finding that, despite technical programs (TS, TD) are shorter than free programs (FS, FD), the longest immersion time (IMmax), the number of the longer immersions (NIM>10s) and their duration (TIM>10s) were actually found in the free programs. This observation may be explained by 1) the rules, which favor prolonged immersions in the free programs (39), 2) the tendency for the free programs to start with the longest possible underwater sequence (29), and 3) the most rated exercise figures, which would imply more repeated and longer IM periods, thus eliciting more frequent and intense bradycardic episodes.

A hierarchical explanatory RPE model

A hierarchical multiple linear regression model (TIM>10s, HR_{min}, and HR_{post5}, and La_{peak}) explained 62% RPE variance (adj. $R_m^2=0.62$; $P<0.001$):

$$\mathbf{RPE = 4.232 + 0.03\ TIM{>}10s + 0.02\ HR_{post5} - 0.01\ HR_{min} + 0.09\ La_{peak}}$$

The first two reflects the influence of long immersions and the subsequent bradycardia, which is consistent with the explanation mentioned above, and the latter two a possible training adaption in this kind of athletes (3, 26, 67, 120). It has been shown previously that trained synchronized swimmers exhibit longer breath hold periods with similar physiological responses but at a lower HR during recovery (3). Thus, synchronized swimmers would be less affected and recover quicker from BH and exercise than woman controls (3). These observations are in accordance with the fact that a faster response in post-exercise HR recovery reflects a positive adaption to exercise training and possibly performance capacity in endurance events (123). In addition, the cardiovascular responses to apnea during dynamic exercise occur also during the recovery period (55). As juniors exhibited significantly higher RPE values than seniors after competitive SS routines (I), the exaggerated diving response and superior apneic ability as a result of their specific training adaptation to apnea appear to have an effect on the perception of effort and, hence, elicited lower scores (II and III). However, longitudinal studies are needed to corroborate such possible training effects. 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.

CONCLUSIONS

1. Hear rate responses during synchronized swimming competitive routines are 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 (I).

2. Moderate blood lactate accumulation appears to be related to 1) the specific influence of the BH periods, 2) the activation of the glycolytic metabolism in the exercising muscles, and 3) the specific training adaptations attributed to influence of the diving response in synchronized swimmers (I).

3. Significant differences in recovery heart rate, blood lactate concentration, and perceived exertion scores, were found among routines regardless of similar peak heart rate. This would support the shared concepts that solo and duet routines are physically more demanding than team routines, and that free routines are generally more so than technical programs (I).

4. The internal load imposed by duet routines performed during training is virtually identical to that elicited in competition. It is suggested that the effects of automaticity—embodied through the replication of the same movement sequence in practice—and the swimmers' long-term adaptations to specific routine exercise and apnea could explain these similarities (II).

5. The use of the CR-10 RPE scale alone does not appear to be a good tool for monitoring the internal load if peak blood lactate concentration or peak heart are used as criterion variables (III). The responsible mechanism of the perceived exertion appears not to be mainly related to

the highest heart rate values attained but, contrarily, to the lowest heart rate during the exercise (bradycardia) as a consequence of long apnea periods (II and III).

6. Prolonged and frequent immersions combined with intense exercise explained 62% of variability in perceived exertion (III), with cardiorespiratory factors providing a relatively greater neural input as compared to metabolic factors (II and III). The results presented in this thesis suggest that specific training adaptation to apnea have a positive effect on the perception of effort (I and III). Longitudinal studies are needed to corroborate such possible training effects.

7. Pre-activation and minimum HR explained 26% of variability in performance (I), rising to 53% when immersion parameters and the lactate concentration in blood were related (III), supporting the idea that an augmented diving response is associated with higher performance in SS. The results presented on this thesis suggest that the higher intensity and the more frequent and longer immersions would be associated with higher merit and performance results (I and III).

FUTURE PERSPECTIVES

The results in this thesis give some indications that there might be a long-term effect of apnea — specific training on the physiological responses in elite SS. In order to further study such possible positive effect of apnea-specific training, longitudinal studies are required. Periodically training measurements of HR and blood lactate concentration on six occasions during the training season have shown a significant decrease both in blood lactate response and minimum HR (120). Concerning RPE, the exaggerated diving response and superior apneic ability as a result of their specific training adaptation to apnea, appear to have also an effect on the perception of effort and, hence, leading them to lower scores (II and III). This simple method has the potential to become a valuable tool for coaches, but practice is necessary to get valid information from this internal load quantification strategy. Thus, a similar but more extensive monitoring of training (i.e. during an entire competitive season) including RPE may provide more information on the behavior of those parameters and corroborate the validity of RPE as a useful tool for intensity control in SS.

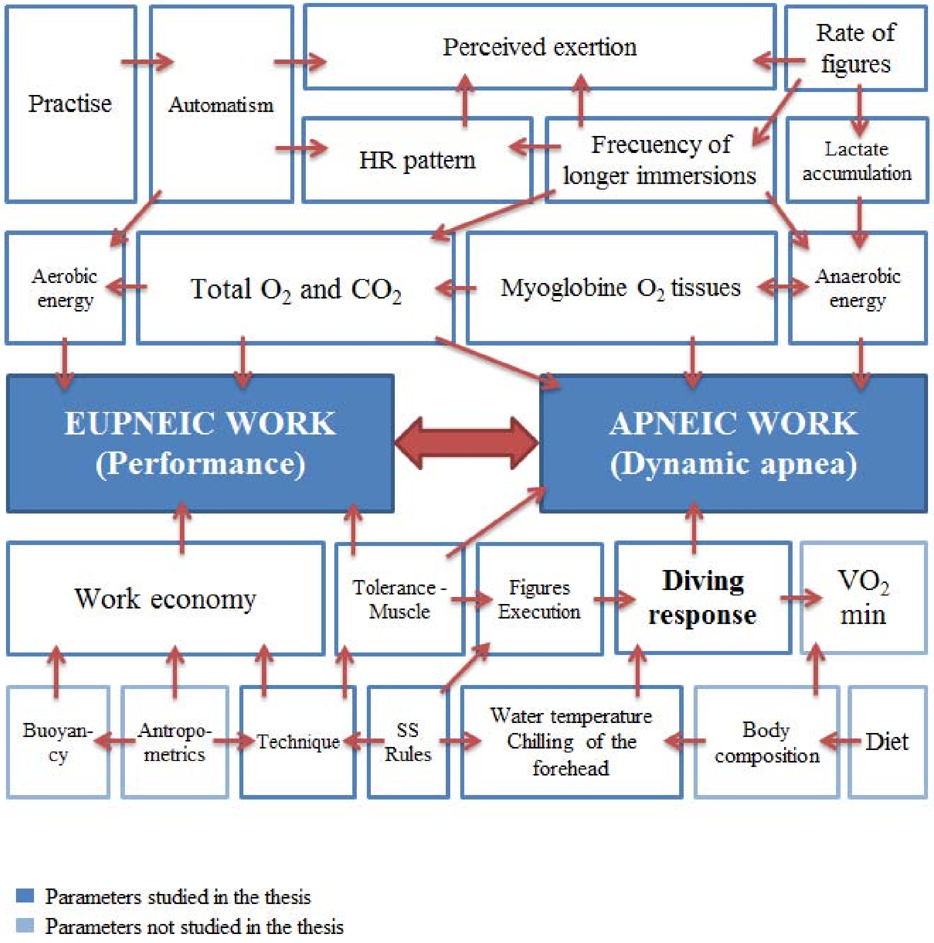
Regarding the external validity of our results, it must be considered that only elite athletes were monitored. It is well known that the degree of bradycardia tends to be higher in synchronized swimmers who are skilled and experienced (57). Then, to elucidate how the cardiovascular response could affect RPE, other populations of synchronized swimmers (e.g., age categories and lower level competitors) and specific group samples from other competitive apnea disciplines (i.e. underwater hockey, underwater rugby, and competitive freediving) would require further investigation.

It is well known that modern SS has become more athletic with the addition of acrobatic elements, increased speed of movement, a requirement for more power, and a greater level of complexity and difficulty in the routines. In modern SS, during the execution of competitive routines, the swimmers’ body position tends to vary a lot. It is known that the possible effects on the cardiovascular changes during apnea are often unaccounted for (81). In this thesis, it was speculated that the most demanding routines (i.e. FS and FD) may have involved harder elements and figures at the start of the routine (I). In addition, the cardiovascular response in SS appears to have an important influence on RPE (III). With this in mind, it is plausible to think that changes on body position during the routine apnea periods would influence not only the cardiovascular responses but also the perceived exertion of the swimmers. To ascertain this possibility, a time motion analysis with a well-established categories study is required.

Finally, with the aim of having a more complete approach to the physiological characterization of the competitive demands in SS, the inclusion of post-exercise oxygen uptake and energy assessment would also be of great interest to ascertain the impact of bradycardia on the oxygen supply to the exercising muscles.

Based on Schagatay (2010) (110) and according to the studies of this thesis and the future perspectives, an overview of the major physiological responses in competitive SS has been proposed (Figure 10).

Figure 10. Factors influencing the physiological responses in competitive SS routines. (Arrows indicating interactions between non-adjacent boxes have been omitted for clarity). Adaptation of Schagatay (2010) (110)



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PAPERS

PAPER I

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Physiological Responses in Relation to Performance during Competition in Elite Synchronized Swimmers

Lara Rodríguez-Zamora[1], Xavier Iglesias[1]*, Anna Barrero[1], Diego Chaverri[1], Pau Erola[2], Ferran A. Rodríguez[1]

1 INEFC-Barcelona Sports Sciences Research Group, Institut Nacional d'Educació Física de Catalunya, Universitat de Barcelona, Barcelona, Spain, **2** Departament d'Enginyeria Informàtica i Matemàtiques, Universitat Rovira i Virgili, Tarragona, Spain

Abstract

Purpose: We aimed to characterize the cardiovascular, lactate and perceived exertion responses in relation to performance during competition in junior and senior elite synchronized swimmers.

Methods: 34 high level senior (21.4±3.6 years) and junior (15.9±1.0) synchronized swimmers were monitored while performing a total of 96 routines during an official national championship in the technical and free solo, duet and team competitive programs. Heart rate was continuously monitored. Peak blood lactate was obtained from serial capillary samples during recovery. Post-exercise rate of perceived exertion was assessed using the Borg CR-10 scale. Total competition scores were obtained from official records.

Results: Data collection was complete in 54 cases. Pre-exercise mean heart rate (beats·min^{-1}) was 129.1±13.1, and quickly increased during the exercise to attain mean peak values of 191.7±8.7, with interspersed bradycardic events down to 88.8±28.5. Mean peak blood lactate (mmol·L^{-1}) was highest in the free solo (8.5±1.8) and free duet (7.6±1.8) and lowest at the free team (6.2±1.9). Mean RPE (0–10+) was higher in juniors (7.8±0.9) than in seniors (7.1±1.4). Multivariate analysis revealed that heart rate before and minimum heart rate during the routine predicted 26% of variability in final total score.

Conclusions: Cardiovascular responses during competition are 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. Moderate blood lactate accumulation suggests an adaptive metabolic response as a result of the specific training adaptations attributed to influence of the diving response in synchronized swimmers. Competitive routines are perceived as very to extremely intense, particularly in the free solo and duets. The magnitude of anticipatory heart rate activation and bradycardic response appear to be related to performance variability.

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* E-mail: xiglesias@gmail.com

Introduction

Synchronized swimming (SS) combines swimming, dancing and gymnastics. Swimmers (in solo, duet or team events) perform synchronized routines of elaborate moves in the water accompanied by music. SS became part of the official Olympic program in 1984, initially in the solo and duet modes, was dropped in 1996 in favor of team competition, and was reintroduced in duet competitions at the 2000 Olympic Games. In each program, swimmers competing above junior level must perform both a technical and a free routine. The technical routine is composed of various required elements that are selected every four years. They are performed in a specific order and last 2 min for the technical solo (TS), 2:20 min:s for the technical duet (TD) and 2:50 min:s for the technical team (TT). The free routine allows more flexibility to demonstrate grace, artistry and creativity, as there are no figure requirements. Its duration is 3 min for the free solo (FS), 3:30 min:s for the free duet (FD), and 4 min for the free team (FT) [1].

In modern SS athletes need to combine technically, physically, and esthetically very demanding exercises, lasting about 2 to 4 minutes, performed at increasingly higher levels of intensity both breathing freely and holding breath. Almost 50% of this time is spent in apnea [2]. Consequently, the sport seems to require high levels of aerobic and anaerobic endurance, as well as exceptional breath control when upside down underwater [3]. Most studies on SS have focused on heart rate (HR) and blood lactate measurements after performing single figures [2,4,5] or a routine training program [6,7]. However, barely any of these assessments have been performed during real competition, making it difficult to derive valid information on the physiological demands of the sport and its different events [3].

Information available on the physiological stress during SS is very scarce and several authors have noted the methodological difficulties to assess physiological parameters during SS performance [8–11]. Others have suggested that physiological testing in elite SS athletes could help determining the modern demands of this sport [12–15]. However, the competitive programs and rules have changed along the years with the addition of acrobatic elements and a greater level of complexity, requiring more speed and power. Today's competitive demands need to be characterized during real competition, thus requiring a field study design, with some intrinsic limitations imposed by the competition rules on the one side, and by the aquatic environment on the other.

In this context, rates of perceived exertion (RPE) have been shown to be a useful tool for determining exercise intensity, as it is related to physiological indicators of exercise stress, including lactate concentration and HR [16]. The Borg CR-10 category-ratio scale [17] has been recently used to quantify training load in swimming [18] and diving [19]. However, we are not aware of any such research in SS competitions.

Accordingly, the aims of the study were a) to describe the cardiovascular, lactate and perceived exertion responses in junior and senior elite synchronized swimmers during an official competition both in technical and free programs, and b) to relate them with SS performance.

Materials and Methods

Study Design

The study was conducted at the 2011 Spanish Absolute Winter Synchronized Swimming Championships. All routines were performed during actual competition with the ad-hoc approval of the Refereeing and Organizing Committees of the RFEN (Royal Spanish Swimming Federation). Most swimmers performed in more than one event, and thus are included in more than one routine group.

Subjects

Thirty-four female synchronized swimmers, including all swimmers in the Spanish National junior and senior teams–among them Olympic (n = 10), and absolute (n = 4) and junior (n = 7) World Championships medalists–volunteered for the study. They all had competed at national and/or international level at least in the previous two years. Twenty-four were juniors (15–18 years) and ten seniors (>18 years), although they were competing at the absolute National Championships and were not classified according to their age category. The physical characteristics of the subjects are presented in table 1. All subjects voluntarily participated in the study after being informed about the scope and methods of the study, and delivered a written informed consent, with parental permission when needed. The study was approved by the Ethics Committee for Clinical Sport Research of Catalonia.

Table 1. Physical characteristics of the subjects.

	All swimmers (n = 34)	Junior (n = 24)	Senior (n = 10)
Height (cm)	165.2±6.5	163.7±5.1	168.9±8.0*
Body mass (kg)	53. 6±5.6	53.2±5.3	54.6±6.3
Age (years)	17.5±3.3	15.9±1.0	21.4±3.6*
Training (h·week^{-1})	33.1±10.0	29.9±8.2	40.7±10.1*
Years of practice (years)	9.6±2.5	8.7±1.5	11.7±3.3*

Values are mean ± SD.

*Significant differences between senior and junior swimmers (unpaired t-test, $P<0.05$).

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Due to restrictions imposed by the official rules and for ecological validity reasons, we were constrained to monitoring HR, post exercise blood lactate concentration, and RPE during competition. The testing protocol is summarized in figure 1. Routines (n = 96) were performed in a 50-m indoor pool (water temperature: 25–26°C) with 30 m available for use. Prior to each competitive session all swimmers performed 45–60 minutes of general warm-up, including swimming, figures, and monitored routine exercises without music. Additionally, 30 min before their participation, all teams were allotted 20 min of specific rehearsal with music, generally involving the execution of the whole routine and selected parts. HR monitors were placed before the warm up and not removed before 15 min after the routine was executed. Capillary blood samples were taken after warm-up and immediately before the call to perform, and 3, 5, 7, and 10 min after each routine. Every routine was assessed and marked by the official judges of the competition according to FINA rules [1]. The total competition score (TCS) for technical routines is composed of separate scores for execution and overall impression; for free routines the TCS is composed of separate scores for technical merit and artistic impression. In both cases, TCS is up to a maximum of 100 points.

Heart Rate Monitoring

HR was measured using waterproof HR monitors (CardioSwim, Freelap, Fleurier, Switzerland), which record beat-by-beat HR and lap times using transmitters' signaling. The belt contains two chest electrodes wired to a monitoring device that can be unloaded on a computer after the recording. Portable beacon transmitters (TX H_2O, Freelap, Fleurier, Switzerland) were placed by the pool at different locations so that the HR monitors' microprocessor units could recall specific positions during competition. To minimize potential instrumentation bias, swimmers wore the HR monitor during training sessions within one 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 5-min recovery period; HR_{peak} and HR_{min} are the highest and lowest 1-s value during the exercise, and HR_{mean} is the arithmetic mean for the competitive routine. Post-exercise HR are the average at minutes 1, 3, and 5 (HR_{post1}, HR_{post3}, HR_{post5}).

Blood Lactate

At every competitive session, following warm-up and a 5-min recovery period and before the call to perform, 10 µL of capillary blood were drawn from the ear lobe. Samples were also taken 3, 5, 7 and 10 min after the routine. Blood samples were immediately analyzed using a lactate photometer (Diaglobal DP100, Berlin, Germany), which had been previously calibrated using lactate standards obtained by dilution (2, 4, 8, 10, 12, 16, and 20 mmol·L^{-1}). The highest value was taken as the peak post-exercise lactate concentration (La_{peak}).

Rate of Perceived Exertion

The Borg CR-10 category-ratio scale was selected to rate the perceived intensity of exertion [17]. A graphical, colored,

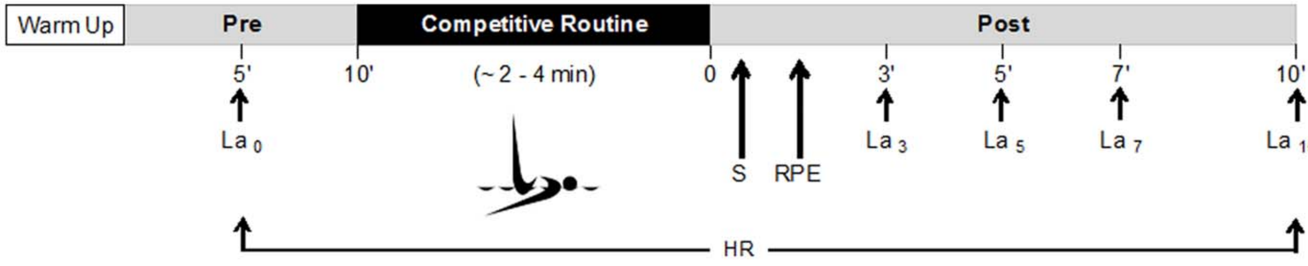

Figure 1. Study protocol. La, blood lactate sample (min); RPE, rating of perceived exertion; S, competition score; HR, heart rate monitoring.
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verbal-anchored scale was shown to the swimmers after completing the routine during blood sampling. The week before competition, all participants were given specific instructions on the meaning and use of the RPE scale, and were assessed repeatedly during at least three training sessions so as to disclose learning effects [18] and to improve the consistency of the measurements.

Video Recording

All routines were continuously recorded using a digital video camera (Panasonic AG-DVX100BE 3-CCD Mini-DV Cinema Camcorder, 50i PAL) at a rate of 50 Hz at a frame rate of 50 fps with an interlaced resolution of 720×576, which allows a time resolution of 0.02 s. For calculations, time values were rounded off to the nearest 0.02 s. The stationary video camera was placed at an elevated site by the pool, just in front of the judges' podium, and perpendicular to the midpoint of the 30 meters area available for competition. 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 by recording HR monitor activation time on the same computer. Blood sampling was timed using conventional chronographs.

Statistical Analysis

Descriptive statistics are mean, standard deviation (±SD), minimum value, and range. Differences in HR, La_{peak}, RPE, and TCS values were analyzed with a mixed multiple ANOVA for fixed effects and interactions (2 age categories and 6 competitive routines, with Bonferroni correction for multiple pairwise comparisons) and Bonferroni post-hoc tests. Pearson's correlation coefficients were calculated between all variables for the entire group of swimmers. Stepwise multiple regression analysis was conducted and best predictive models developed ($P_{in} = 0.05$, $P_{out} = 0.10$), with TSC (performance) as dependent variable and all physiological parameters as predictor variables. Precise P values are reported and $P<0.05$ was considered significant.

Results

Although 96 routines were actually monitored, data collection was complete only in 54 cases, which were those finally included in the statistical analysis; the majority of missing values corresponded to failed or poor quality HR recordings.

Heart Rate

Figure 2 shows an example of a HR response profile before, during, and after a competitive free duet routine on an elite synchronized swimmer (Olympic and World medalist) in which, after a period of anticipatory pre-activation, HR quickly and progressively increases to high levels of tachycardia, interspersed with periods of intense bradycardia during the intense exercise bouts performed while in apnea.

The pattern of HR response during the execution of the six routine programs (table 2) was similar in most of the HR parameters for the entire group of swimmers. However, significant differences were noted in recovery HR (HR_{post3} and HR_{post5}) between the TS and the FT routines ($P<0.01$). Likewise, HR_{post3} was higher in TD as compared to FT routines ($P<0.01$).

Although HR_{pre} was significantly higher in juniors than in seniors (135.7±10.6 vs. 119.6±10.6 $\text{beats}\cdot\text{min}^{-1}$, $P<0.001$), no differences were found within routines for the junior (table 3) or senior (table 4) groups.

Blood Lactate

For the entire group of swimmers, resting blood lactate was 1.72±0.49 $\text{mmol}\cdot\text{L}^{-1}$. Maximal values were attained at the 5th or 7th min during the recovery period in all cases. Table 5 summarizes La_{peak} values for each routine program. For the entire group of swimmers La_{peak} was higher in the FS routine (8.5±1.8 $\text{mmol}\cdot\text{L}^{-1}$) than in the TD (6.8±1.8 $\text{mmol}\cdot\text{L}^{-1}$, $P<0.01$) and FT (6.2±1.9 $\text{mmol}\cdot\text{L}^{-1}$, $P<0.001$). La_{peak} was also significantly higher in the FD (7.6±1.8 $\text{mmol}\cdot\text{L}^{-1}$) than in the FT (6.2±1.9 $\text{mmol}\cdot\text{L}^{-1}$, $P<0.01$) routines. No significant differences were noted between juniors and seniors (6.7±2.0 and 7.4±2.1 $\text{mmol}\cdot\text{L}^{-1}$, respectively).

RPE Score

Mean RPE scores (0–10+) are shown in table 5. For the entire group of swimmers, values for FS (8.0±0.9) and FD (8.1±0.9) exercises were higher than both team routines (FT 7.5±1.1, $P<0.05$, and TT 6.6±1.2, $P<0.01$). In both duet routines, FD (8.1±0.9) and TD (7.6±0.9), scores were higher than in TT (6.6±1.2, $P<0.01$). RPE scores were significantly higher in juniors (7.8±0.9) than in seniors (7.0±1.4, $P<0.05$). No differences were noted among routines in the junior group. In the senior group, RPE values were higher in the FS routine (8.5±0.5) than in both team routines (FT 6.1±1.1, TT 5.7±0.5, $P<0.001$). TS (7.3±2.0) and FD (7.8±1.0) elicited higher RPE values than TT (5.7±0.5, $P<0.01$).

Total Competition Score

Mean TSC (points) across all routines are presented in table 6. Swimmers attained higher scores in the FT (84.0±4.2) than in the TD (81.0±5.7, $P<0.01$). Even if this was an absolute competition, seniors (87.0±5 points) were rated higher than juniors (79.1±3.4, $P<0.001$).

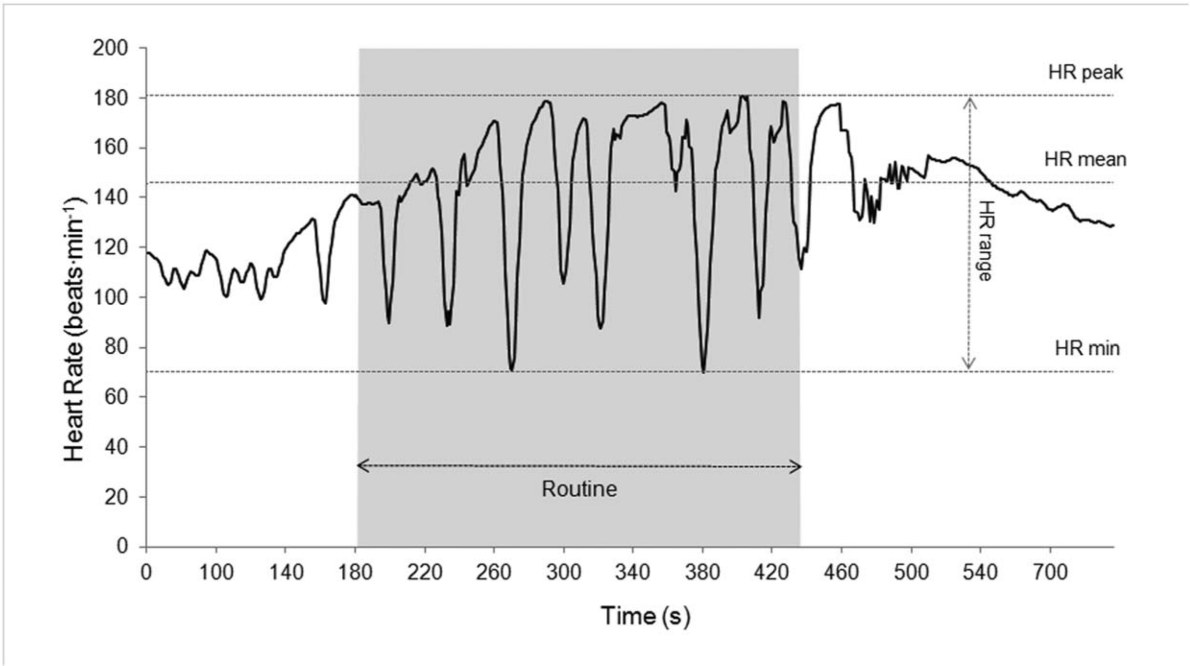

Figure 2. Heart rate profile before, during, and after a competitive free duet routine on an Olympic and World medalist. HR peak, heart rate peak during the routine; HR range, heart rate difference between the minimum heart rate and the maximum value during the routine; HR min, minimum heart rate during the routine; HR mean, the average heart rate during the routine. Line depicts smoothed 5-s averaged values for clarity.
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Physiological Correlates of Performance

TCS performance scores negatively correlated with HR_{pre} ($R = -0.41$; $P<0.001$) and HR_{min} ($R = -0.24$; $P<0.05$), and positively correlated with HR_{range} ($R = 0.22$; $P<0.05$). In the stepwise multiple regression analysis the best model included only HR_{pre} and HR_{min} ($R_m{}^2 = 0.26$; $P<0.0001$; $SEE = 4.86$). No other significant bivariate or multivariate correlations were found between TCS and the rest of HR, La_{peak}, and RPE variables.

Discussion

To our knowledge, this is the first study in which the physiological responses to SS routines during an official competition in high-level swimmers are characterized. We found a very intense anticipatory HR pre-activation in all swimmers, even more pronounced in juniors. During the execution of all routines in both age-category groups, cardiovascular demands were equally high, with HR quickly approaching maximal levels, and interspersed periods of marked bradycardia during the intense exercise bouts performed in apnea. In contrast, differences were noted among routines in blood lactate levels, with highest values in free solo,

Table 2. Heart rate (HR) parameters before (Pre), during (Routine), and after (Post) the competitive routines for the entire group of swimmers.

		TS	FS	TD	FD	TT	FT	All Routines
		(n = 5)	(n = 6)	(n = 10)	(n = 9)	(n = 5)	(n = 24)	(n = 59)
Pre	HR_{pre}	122.3±10.8	130.5±15.9	124.6±12.5	130.7±9.6	125.9±10.1	132.0±14.7	129.1±13.1
Routine	HR_{peak}	195.5±8.3	189.3±7.6	191.8±10.9	192.5±14.4	192.4±7.3	191.2±5.6	191.7±8.7
	HR_{mean}	156.9±9.1	150.1±21.1	161.2±13.1	153.1±20.2	167.2±7.4	162.5±11.6	159.6±14.4
	HR_{min}	93.1±21.7	71.4±35.4	94.5±28.1	85.4±27.7	91.2±13.8	89.3±31.3	88.8±28.5
	HR_{range}	102.4±17.8	118±34	97.2±25.2	107.1±32.6	101.2±18.8	101.9±31.9	103.5±28.7
Post	HR_{post1}	146.6±21.9	146.5±24.1	157.6±12.5	155.3±21.5	155.6±17.0	152.0±35.9	152.7±26.7
	HR_{post3}	108.0±12.8	117.8±11.5	113.0±13.7	130.4±7.1	123.1±12.9	128.8±11.0^{a,b}	122.9±13.4
	HR_{post5}	88.3±18.1	105.1±4.9	103.2±8.3	111.0±15.5	110.5±9.0	113.6±12.2^{a}	108.1±13.6

Data are mean ± SD (beats·min^{-1}). TS, Technical Solo; FS, Free Solo; TD, Technical Duet; FD, Free Duet; TT, Technical Team; FT, Free Team. HR_{pre}, last minute before routine; HR_{peak}, HR_{mean}, HR_{min}, HR_{range}: peak, mean, minimum, and range values during routine; HR_{post1}, HR_{post3}, HR_{post5}: first, third and fifth minutes during recovery. Significant differences ($P<0.05$) among routine programs were noted only during recovery: ^{a}FT vs. TS; ^{b}FT vs. TD.
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Table 3. Heart rate (HR) parameters before (Pre), during (Routine), and after (Post) the competitive routines for junior category.

		TS	FS	TD	FD	TT	FT	All Routines
		(n = 2)	(n = 1)	(n = 4)	(n = 8)	(n = 2)	(n = 17)	(n = 34)
Pre	HR_{pre}	130. 8±14.2	153.4	135.4±6.1	131.5±9.9	133.8±0.2	137.6±11.5	135.7±10.6
Routine	HR_{peak}	202.7±2.7	180.4	189.1±8.0	191.4±14.9	193.3±14.1	190.8±5.0	191.3±9.2
	HR_{mean}	158.5±3.0	149.3	164.4±15.4	150.4±19.8	170.2±12.9	166.1±7.4	161.5±13.6
	HR_{min}	97.0±12.1	56.5	90.1±25.0	81.9±27.3	84.0±9.8	96.7±26.7	90.5±25.4
	HR_{range}	105.8±14.8	123.9	98.9±17.8	109.5±34.0	109.3±23.8	94.1±25.7	100.7±26.1
Post	HR_{post1}	135.9±21.0	160.8	167.4±8.2	154.1±22.6	153.1±31.9	158.3±33.8	156.9±27.5
	HR_{post3}	98.7±18.5	106.0	118.7±16.7	130.5±7.6	136.7±0.1	129.8±11.7	126.4±14.3
	HR_{post5}	74.2±17.4	101.3	108.7±5.2	111.4±16.5	119.2±0.5	113.5±13.8	110.2±15.9

Data are mean ± SD (beats·min^{-1}). TS, Technical Solo; FS, Free Solo; TD, Technical Duet; FD, Free Duet; TT, Technical Team; FT, Free Team. HR_{pre}, last minute before routine; HR_{peak}, HR_{mean}, HR_{min}, HR_{range}: peak, mean, minimum, and range values during routine; HR_{post1}, HR_{post3}, HR_{post5}: first, third and fifth minutes during recovery.

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followed by free duets and technical and team routines. Both HR pre-activation and bradycardia were moderately related to performance.

Heart Rate Response

A remarkably high HR pre-activation was observed in all subjects and routines (table 2). This conspicuous HR dynamics alteration before the actual start of the exercise is likely due to: 1) the effect of the previous warm up, 2) the sympathetic activation and parasympathetic withdrawal necessary to ensure anticipatory metabolic and cardiovascular responses to a physical effort [20], and 3) the mental stress and anxiety associated with competition proximity [21,22]. This anticipatory HR response was even more pronounced in the junior group (about 8 beats·min^{-1} higher on average) suggesting that senior synchronized swimmers might be better adapted to competition stress due to higher competitive experience and/or specific training. This is in accordance with the conscious processing hypothesis [23], which states that stress affects performance through a process in which anxiety induces a conscious reinvestment of explicit knowledge to control the execution of the skill and, paradoxically, disrupts the automaticity of performance. This limitation in performance has been consistently reported in relation to self-focused (internal) attention [24,25]. Internal attentional focus constrains the motor system by interfering with natural control processes, whereas an external focus seems to allow automatic control processes to regulate the movements associated with optimal performance and is typically found in expert-level athletes [26]. An alternative explanation is that in competitive situations novice performers are highly motivated to do well and this leads to a tendency to focus on the process of performing [27]. Thus, junior swimmers, who may be more aware of the importance of precise skill execution, would have attempted to ensure success by more consciously monitoring their performance. On the contrary, the attainment of a higher skill level (i.e. typically in seniors swimmers), would be associated with a greater automaticity in performing motor acts, related to a lower metabolic energy cost for achieving the task goal, thus reducing attentional demands and using an energy-efficient preferred mode [28–30], which in turn would imply a blunted HR pre-activation response. Present results are consistent with previous findings in highly skilled golfers in comparison to novice players [31–33]. In short, competitive experience and years of training would have an effect on swimmers' anticipatory HR pre-activation related to higher levels of automaticity in task performance, lower levels of anxiety prior to competition, and a different pattern of attentional focus. A unique aspect of SS is the frequent and often lengthy breath holding (BH) periods while performing high-intensity exercise underwater. A key finding of

Table 4. Heart rate (HR) parameters before (Pre), during (Routine), and after (Post) the competitive routines for senior category.

		TS	FS	TD	FD	TT	FT	All Routines
		(n = 3)	(n = 5)	(n = 6)	(n = 1)	(n = 3)	(n = 7)	(n = 25)
Pre	HR_{pre}	116.7±3.7	125.9±12.5	117.4±10.2	124.4	120.6±9.9	118.4±13.2	119.9±10.6
Routine	HR_{peak}	190.6±6.7	191.1±7.0	193.5±12.9	201.5	191.9±2.3	192.1±7.3	192.4±8.0
	HR_{mean}	155.8±12.5	150.2±23.6	159.1±12.3	174.7	165.2±3.4	153.7±15.5	156.8±15.3
	HR_{min}	90.5±29.0	74.3±38.7	97.4±31.9	113.9	96.1±15.7	71.1±36.1	85.1±32.4
	HR_{range}	100.1±22.5	116.7±37.8	96.2±30.8	87.6	95.8±17.7	120.9±39.1	107.3±32.1
Post	HR_{post1}	153.7±23.4	143.6±25.8	151.1±10.5	164.8	157.2±7.7	136.5±38.7	147.1±25.0
	HR_{post3}	114.2±3.3	121.1±9.2	109.2±11.2	129.5	114.0±4.5	126.0±9.2	118.3±10.7
	HR_{post5}	104.9±5.4	99.6±8.2	99.6±8.2	107.3	104.7±5.9	113.9±7.9	105.4±9.4

Data are mean ± SD (beats·min^{-1}). TS, Technical Solo; FS, Free Solo; TD, Technical Duet; FD, Free Duet; TT, Technical Team; FT, Free Team. HR_{pre}, last minute before routine; HR_{peak}, HR_{mean}, HR_{min}, HR_{range}: peak, mean, minimum, and range values during routine; HR_{post1}, HR_{post3}, HR_{post5}: first, third and fifth minutes during recovery.

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Table 5. Peak blood lactate (La_{peak}), and rates of perceived exertion (RPE) of the routines.

Category	Variable	TS	FS	TD	FD	TT	FT	All Routines
		(n = 9)	(n = 11)	(n = 16)	(n = 16)	(n = 14)	(n = 30)	(n = 96)
All swimmers	La_{peak} (mmol·L^{-1})	6.9±1.4	8.5±1.8^{b}	6.8±1.8	7.6±1.8	7.1±2.4	6.2±1.9^{a}	7.3±2.0
	RPE (a.u.)	7.1±1.7	8.0±0.9	7.6±0.9	8.1±0.9	6.6±1.2^{d}	7.5±1.1^{c,e}	7.0±1.4
Junior	La_{peak} (mmol·L^{-1})	6.1±1.1	8.1±3.3	6.5±1.5	6.9±1.7	7.0±2.7	6.5±1.9	6.7±2.0
	RPE (a.u.)	6.7±1.2	7.4±0.9	8.1±0.6	8.2±0.9	7.4±1.1	7.9±0.8	7.8±0.9*
Senior	La_{peak} (mmol·L^{-1})	7.4±1.5	8.8±1.7	7.0±2.2	8.8±1.4	7.2±2.2	5.3±1.7	7.4±2.1
	RPE (a.u.)	7.3±2.0	8.5±0.5^{h}	7.0±0.8	7.8±1.0^{i}	5.7±0.5^{f}	6.1±1.1^{g}	7.1±1.4

Values are mean ± SD. TS, Technical Solo; FS, Free Solo; TD, Technical Duet; FD, Free Duet; TT, Technical Team; FT, Free Team; a.u., arbitrary units (0–10+).
*Significant differences between junior and senior swimmers for all routines. Significant differences among routines in:
La_{peak} ($P<0.05$) for all swimmers are: [a]FT vs. FD and FS; [b]FS vs. TD.
RPE for all swimmers are: [c]FT vs. FS; [d]TT vs. FS, TD and FD; [e]FT vs. FD.
RPE ($P<0.05$) for the senior group are: [f]TT vs. TS, FS and FD; [g]FT vs. FS and FD; [h]FS vs. TD; [i]TD vs. TT.
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this study is that the main cardiovascular response to BH (i.e. bradycardia) was powerful enough to counteract the HR response during the BH phases of intense exercise (figure 2). It is well known that BH has marked effects on blood pressure (BP), cardiac output, and HR during and after dynamic exercise, which do not seem primarily induced by the resulting hypoxia, where the respiratory arrest *per se* is essential for these cardiovascular responses [34,35]. Dynamic apnea, as observed for instance in free diving competitions, has shown to induce an increase in BP, which stimulates the circulatory baroreceptors provoking bradycardia, peripheral vasoconstriction and reduced cardiac output, thus decreasing oxygen uptake [36]. These responses would result in restricted muscle metabolism and blood flow redistribution to areas where demands are greatest in order to allow sustained function [37]. However, BH epochs may respond not only to underwater immersion, but also to face water immersion [38], as well as to isometric contraction of the core muscles causing a Valsalva effect.

Thus, during SS, the diving response appears to be powerful enough to override the HR response to exercise during apnea. Cardiac output is expected to be reduced throughout dynamic apneas, largely due to bradycardia, whereas the systemic vascular resistance would increase [36]. These cardiovascular responses are obviously interplaying during water immersion and BH phases of SS routines due to intense exercise combined with BH, which would produce a rapid development of hypercapnia and hypoxia [35]. While apnea and facial immersion increase the parasympathetic tone causing HR reduction [34,39], exercise increases sympathetic stimulation of the heart [3] and increases HR. So when the swimmer starts holding breath during the routines, both inputs compete with each other for control of HR [40] 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.

The observed periods of bradycardia in our swimmers, who reached minimum HR of 75–95 beats·min^{-1} on average (mean 46% HR reduction) were similar to those found during dynamic apnea diving [35,40,41], and in SS during training exercises [3,5,13,42], and was more pronounced than the 38% relative HR reduction observed during face immersion during low-intensity (80 and 100 W) cycling exercise [36,43]. We should take into account that while synchronized swimmers perform several movements combining isometric and intense dynamic exercise, in most previous studies the subjects performed low-intensity, steady-state exercise with face immersion in water to elicit the diving response. Hence, the combination of movements in the pool, with sequential or simultaneous jumps, strokes, acrobatics, and diving across the

Table 6. Total competition score and duration of the competitive routines (time).

Category	Variable	TS	FS	TD	FD	TT	FT	All Routines
		(n = 9)	(n = 11)	(n = 16)	(n = 16)	(n = 14)	(n = 30)	(n = 96)
All swimmers	TCS (points)	81.6±7.2	82.3±7.5	81.0±5.7	82.4±6.6	81.5±5.3	84.0±4.2^{a}	82.3±5.7
	Time (min:s)	2:05±0:08	2:58±0:06	2:29±0:06	3:30±0:11	3:00±0:05	4:05±0:06	–
Junior	TCS (points)	75.7±4.5	76.2±3.4	78. 4±3.1	78.0±2.6	78.5±3.7	81.1±2.5^{b}	79.1±3.4*
	Time (min:s)	1:56±0:10	2:58±0:04	2:27±0:07	3:28±0:09	2:57±0:03	4:04±0:05	–
Senior	TCS (points)	87.5±4.5	88.3±4.8^{c}	85.3±5.7	87.8±6.6	85.8±4.2	88.1±4.5	87.0±5
	Time (min:s)	2:09±0:04	2:58±0:08	2:30±0:06	3:34±0:14	3:03±0:04	4:11±0:06	–

Data are mean ± SD. TS, Technical Solo; FS, Free Solo; TD, Technical Duet; FD, Free Duet; TT, Technical Team; FT, Free Team; TCS, total competition score.*Significant differences between junior and senior swimmers for all routines.
Significant differences ($P<0.05$) are:
For all swimmers: [a]FT vs. TD.
Among juniors: [b]FT vs. TS, FS, TD and FD.
Among seniors: [c]FS vs. TT.
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SS routines, yields HR values proportional to exercise intensity but also induces a bradycardic response similar to diving alone [15] or combined with low intensity exercise [35].

In all routines, high HR_{peak} values indicated a very intense activation of the cardiovascular system to ensure the high-energy turnover in the exercising muscles. These values are higher than previously reported by Jamnik (1987) [3] who found HR_{peak} values ranging from 161 to 180 beats·min^{-1} during solo, duet and team training routine exercises, as well as compared to 178.0±4.2 and 179.5±4.9 beats·min^{-1} during technical and free duets shown by the same two elite swimmers reported by Pazikas et al. (2005) [13]. They are also higher than those observed during a simulated training routine consisting on standard SS maneuvers executed while swimming in straight lines up and down the pool during 4.5 minutes (176±7 beat·min^{-1}) [6]. We found no references in literature that can be directly comparable with present results. During competition, HR rapidly increases showing an underlying pattern of exponential increase to asymptotic maximal levels with marked bradycardic episodes (figure 2). This suggests that BH oxygen conservation mechanisms do not prevent the activation of the cardiorespiratory system to provide energy for the exercising muscles despite blunting the HR response during the periods of apnea.

The fact that we found no differences in HR_{peak} between juniors and seniors is likely to be an indication that all routines were performed at maximal intensity by all swimmers despite the observed differences in performance as quantified by final competition scores. Interestingly, no differences in HR_{peak} among the different routine programs were noted despite the wide range of exercise duration (roughly 2 to 4 min), in contrast with significant differences in recovery HR, La_{peak}, and RPE, which would support the shared concepts that solo and duet routines are physically more demanding than team routines, and that free routines are generally more so than technical programs.

With respect to HR recovery parameters (HR_{post3} and HR_{post5}), the FT routines show a slower off-kinetics then TS. We can only propose a plausible explanation to this observation, which is the lower average cardiorespiratory fitness in team swimmers as compared to soloists (all of them World medalists in our sample). This would be in accordance with previous findings showing that a lower HR during recovery is a specific adaptation in trained synchronized swimmers [15]. Likewise, since both category groups exhibited similar HR off-dynamics, junior and senior swimmers in this study seemed to be similarly adapted to SS training. Whether this adaptation derived from similar levels of general cardiorespiratory fitness or to an enhanced ability to breath hold as a specific feature of SS training adaptation [15] could not be elucidated.

In summary, cardiovascular demands of all SS competitive routines, which are described for the first time during actual competition in a large number of subjects, can be best described as very high, regardless of its duration and technical content. Since the HR response is largely depending on BH responses, it seems logical to assume that non-specific laboratory tests would not accurately reproduce specific cardiovascular loading and hence miss an important feature of specific adaptation to SS performance. Simulated routines with high technical content in a training environment would seem to be a better approach if these adaptations should be assessed or elicited. However, we must realize that HR–even if a practical and measurable indicator of the cardiorespiratory adaptation to physical effort–is influenced by many physiological factors during this unique combination of intense, finely coordinated exercise, frequent apneic periods, and sudden changes in body position. They call into play simple reactions (e.g. diving reflex, Valsalva reflex) and complex regulatory mechanisms (e.g. brain and muscle perfusion, cardiac output and blood pressure regulation).

Blood Lactate

Elite synchronized swimmers are exposed to hypoxia because of the combination of BH and vigorous exercise [44]. However, the present results indicated moderate La_{peak} in both age categories, ranging from ~5 to 13 mmol·L^{-1}, with an overall average of 7.3 mmol·L^{-1} (table 5). La_{peak} data from competition are very scarce. Although reports on lactate levels during training are more extensive [3,6–8,14], only Jamnik et al. (1987) [3] reported an intriguing average of 12.7±1.3 mmol·L^{-1} in five elite swimmers, surprisingly higher than the 7.0±1.3 mmol·L^{-1} when performing the same routine during practice.

The highest La_{peak} values were obtained in free solo and duet programs. These observations can be analyzed in terms of 1) the specific influence of the BH periods, 2) the activation of the glycolytic metabolism in the exercising muscles, and 3) the specific training adaptations.

First, the peripheral vasoconstriction associated with the diving response during the BH periods would reduce the blood supply to the muscles and lower their O_2 stores and, as a consequence, if the energy turnover in the exercising muscles is sustained or increased, the glycolytic metabolism will be activated and more lactic acid be produced [43,45,46]. Homma et al. (1994) [2] showed that the time spent underwater in international competitions was highest in solo (62.2%), duets (56.1%), and teams (51.2%). Then we could speculate that the more reduced peripheral O_2 delivery due to the longer or more frequent BH times [2,42], the higher the lactate production due to hypoxemia. This seems consistent with our observation that free solo and duet routines induced the highest La_{peak} values as compared with the team and technical routines. From a mechanistic perspective, moderate lactic acidosis would decrease the affinity of myoglobin and hemoglobin for O_2, thus facilitating O_2 diffusion to muscle mitochondria for sustained oxidative phosphorylation during the apneic bouts. Thus, with progressive lactate accumulation during the routines, increased O_2 supply may be made available, leading to prolongation of oxidative metabolism in parallel with anaerobic glycolysis [37]. Moreover, our findings are in line with previous studies in eupneic aesthetic sports such as rhythmic and sport gymnastic events of shorter duration (~1.5 min), e.g. competitive aerobic (7.5 mmol·L^{-1}) [47], floor exercises in artistic gymnastics (8.5 mmol·L^{-1}) [48], but also with longer events (~4.5 min) such as figure ice skating (7.4 mmol·L^{-1}) [49]. Nevertheless, higher average values have been described after competition in disciplines with an intermittent respiration pattern and similar duration, such as 200 m freestyle swimming (10.5 mmol·L^{-1}) [50], surf lifesaving (9.0 mmol·l^{-1}) [51], and even in competitive dynamic apneas (10.0 mmol·l^{-1}), in which apneic duration is essential and needs to be prolonged by any means to increase gas storage or tolerance to asphyxia. In contrast, we noted no difference between our data and those attained by elite underwater hockey players (8.0 mmol·L^{-1}) [52]. These results may be explained by the specific training pattern of SS, characterized by frequent and intense bouts of dynamic apnea interspersed by short breaths with relatively low tidal volumes compared with free divers. Such differences may indicate that during eupneic work, part of the lactate produced in the working muscles is rapidly catabolized by the less active muscles and other tissues, or used during recovery to resynthesize glycogen. However during 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 [37].

Second, we should avoid interpreting the La_{peak} values in terms of the sole variations of its cellular production because lactate in capillary blood samples will reflect the balance between production and catabolism (mainly intracellular and in other organs and less active muscles) [53]. The higher La_{peak} values obtained in FS and FD competitive routines (~3–3.5 min) suggest a more intense activation of anaerobic glycolysis [14]. Empirically, many coaches and swimmers believe that FS and FD are the most strenuous routine programs. Our data do support this concept, as La_{peak} is highest in free solo and duet. Several hypotheses can be advanced to explain these results. On the one hand, free programs usually start with an underwater sequence which may last in excess of 45 s in the case of more highly placed contestants [44]. In spite of blood flow redistribution, O_2 stores might be reduced at the onset of the routine and, hence, the working muscles would receive less O_2 than required due to peripheral vasoconstriction and would then rely more on glycolytic metabolism. On the other hand, the rate of execution of skill elements tends to be higher in the solo event than in duet and team [2]. In fact, in solos, 50% of the technical merit score depend on the execution [1], then not being surprising that this event is composed of more figure parts implying a higher physiological stress than duets (51.9%) and teams (32.2%) [2,5]. Especially in duets, swimmers generate actions requiring constant fine-tuned synchronization with music and couples [54]. Moreover, the difficulty and order of the figures could have also influenced the course of activation of the glycolytic metabolism in the exercising muscles. We could only speculate that FS and FD routines may have involved harder elements and figures at the start of the routine with the concomitant increase in the workload, which would result in higher lactate formation. This possibility should be addressed in the above mentioned time-motion analysis.

Third, La_{peak} values indicate an equally moderate blood lactate accumulation in juniors and seniors, evidencing a similar role of the anaerobic metabolism in energy delivery during SS, as suggested by previous studies [8,10]. This may be explained by the fact that both age categories executed similar technical elements during the routines as they were participating in an absolute championship and judged under the same rules, implying the execution of the same mandatory technical figures performed in the same order within a similar time frame [1]. These results suggest similar metabolic training adaptations between both age groups despite the higher training volume of the senior swimmers. Moreover, there are some similarities between our data and those reported by authors who studied the effects of SS training in blood lactate levels, who found a significant decrease in La_{peak} along a season [6,7]. Training practice seems to produce such adaptations improving effectiveness at both peak and submaximal exercise [55], and could explain the improvements in work economy by promoting greater technique skills.

In short, this study shows a moderate post-routine blood accumulation in elite senior and junior synchronized swimmers, likely to result from the large number of figures and high execution rate [10], paralleled by reduced peripheral O_2 delivery due to BH periods and the subsequent diving response [2,42], and an adaptive mechanism to assure central oxygenation. At this time, one may only speculate on the progressive development of an adaptive metabolic response in synchronized swimmers to repetitive apneas, which should be explored using longitudinal studies.

Rate of Perceived Exertion

RPE has been defined as the subjective intensity of effort, strain, discomfort, and/or fatigue that is experienced during physical exercise [56]. It has been suggested that the inputs for perceived exertion can be categorized into those of central and peripheral origin [57]. Central factors 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.

The CR-10 category ratio scale developed by Borg [58] appears to be one of the best choices regarding its psychometric characteristics and criterion-related validity [16]. However, RPE scales have barely been used during real competition in short-duration events, and never in SS. Only one study reported RPE (6–20 scale) during an international-level taekwondo competition and found near-maximal HR, high blood lactate levels, and increases in competitors' RPE across combats [59]. Mean RPE values in the present study ranged from 6.6 (TT) to 8.1 (FD), with quite large inter-individual range of variation (table 5). These scores corresponded to "very strong" to "extremely strong" verbal-anchored levels, with only 3% of the swimmers reaching the absolute maximum intensity (i.e. 10+). Contrarily to HR and La_{peak} levels, RPE values were significantly higher in juniors than in seniors, hence indicating that seniors perceived their performance to be less strenuous. This can be explained by the greater number of years in training and the superior competitive experience in the senior group. This concept is supported by the observation that, while no differences were noted among routines in the junior group, FS and FD routines elicited the highest scores and team routines the lowest in the senior group, and corresponded well to La_{peak} values. In fact, RPE was positively correlated with La_{peak} ($R = 0.26$), particularly when controlling for age category ($R = 0.55$). On the one side, based on a recently published meta-analysis [16], RPE scores (CR-10) have been found to be poorly correlated both with HR or blood lactate (mean $R = 0.47$ and 0.42, respectively), even if the mode of exercise used in previous studies were mostly progressive or intermittent running, walking, or swimming.

Performance and Physiological Correlates

The relationship between cardiac parameters and performance showed that a higher skill level was associated with a lower anticipatory HR activation and lower levels of bradycardia, with subsequent higher HR range of variation. These relationships are consistent with the notion that the attainment of a proficient level of expertise in SS is related to an improvement of motor automaticity and reduced attentional demands [26,60], and also to specific physiological responses to apnea training, as suggested by previous studies [52,61].

Lower anticipatory HR activation, which has been reported in tasks with high external attentional focus, was associated to performance improvements in self-paced sport activities such as rifle and pistol shooting, archery and golf. Our findings are in line with these results. The observed negative correlation between HR_{pre} and performance would reflect decreased afferent inputs to the brain and would result in more effective external focusing of attention and superior performance [62,63]. Moreover, it appears that juniors, who achieve higher HR anticipatory activation, were putting greater attentional effort to the routine tasks (i.e. internal attentional focus) than seniors, although resulting in lower levels of performance.

A second explanation for increased anticipatory HR activation in the junior swimmers would rather reflect differences in cardiorespiratory responses. On the one side, the anticipatory tachycardic response and hyperventilation may be effective in preparing the body (particularly the O_2 delivery system) for maximal effort. On the other side, an elevated metabolic rate would further reduce the limited O_2 stores during apnea. As discussed before, the O_2-conserving effect of the diving response is explained by a reduction in cardiac output and a redistribution of peripheral blood flow. A decrease in cardiac output during apnea would reduce the pulmonary O_2 uptake [43,64]. Thus, during apnea, the rate of arterial O_2 desaturation is affected by factors related to the size of the O_2 stores at the beginning, and to the rate of O_2 usage during exercise [41]. Since the anticipatory HR response is thought to increase the cardiac output before starting the exercise, this would consequently increase the rate of O2 depletion and could limit aerobic performance. This is also consistent with our observation that junior swimmers have higher anticipatory HR pre-activation and lower performance.

On the other hand, we noted an inverse relationship between the level of bradycardia and HR range of variation with performance. It can be hypothesized that a more pronounced bradycardic response–and hence lower HR_{min} and higher HR_{range}–may be related to more prolonged BH periods in higher rated routine exercises or to a sharper decrease in HR as a consequence of the increased O_2 conservation effect in the more experienced swimmers [15]. Bradycardia is an essential protective reaction of the cardiac system aimed at economically managing O_2 levels during BH [65]. The economical use of O_2 results from lowered myocardial O_2 demands causing a decrease of the cardiac output [66]. It is well known that long-term apnea training increases hematocrit, erythropoietin concentration, hemoglobin mass, and lung volumes [39,67,68] indicating adaptation to hypoxia. An augmented diving response is associated with a reduced rate of arterial desaturation and a reduced rate of depletion of the lung O_2 stores during apnea at both rest and exercise, which is thought to reflect the O_2-conserving effect of the human diving response [38,43,64,69]. In SS this mechanism aims to maintain the O_2 delivery in support of the most vital functions of heart, brain, and lungs. Our results are in accordance with the observations of pronounced bradycardia in professional skin divers [38], and underwater hockey players [52], suggesting that their exaggerated diving response and superior apneic ability is at least in part a product of their apnea training.

Globally, the fact that the multivariate model included two HR parameters (HR_{pre} and HR_{min}) and explained 26% of variability in performance (TCS) supports the concept that an augmented diving response is associated to superior performance in SS. However the conclusion that an augmented diving response is beneficial for SS performance clearly requires further study.

Conclusions

Cardiovascular responses during competition are 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. Moderate blood lactate accumulation appears to be related to the number of figures, execution rate, apneic periods and exercise duration, and suggests an adaptive metabolic response as a result of specific training adaptations attributed to influence of the diving response in synchronized swimmers. Competitive routines are perceived as very to extremely intense by all swimmers, likely reflecting not only the absolute exercise demands but also their previous experience and expectations. HR anticipatory activation and bradycardic appear to be related to the variability of performance in SS, which seems to be associated to more pronounced bradycardic response. However, the role of BH and diving in the physiological response to very intense dynamic exercise warrants further investigation.

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Author Contributions

Conceived and designed the experiments: LRZ XI FAR. Performed the experiments: LRZ XI DC AB PE FAR. Analyzed the data: LRZ XI DC AB PE FAR. Wrote the paper: LRZ XI FAR.

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PAPER II

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Monitoring internal load parameters during competitivesynchronized swimming duet routines in elite athletes

Lara Rodríguez-Zamora, Xavier Iglesias, Anna Barrero, Lorena Torres, Diego Chaverri, Ferran A. Rodríguez

[1]INEFC-Barcelona SportsSciencesResearchGroup, Institut Nacional d’Educació Física de Catalunya, Universitat de Barcelona, Spain

✉ Xavier Iglesias
INEFC
Avda. de l’Estadi, 12-22 (Anella Olímpica de Montjuïc)
08038 Barcelona, Spain
Phone +34 934255445 (ext. 260); Fax +34 934263617
xiglesias@gmail.com

Running head: Internal load in synchronized swimming

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ABSTRACT

The aim of the study is to compare the heart rate (HR) and rate of perceived exertion (RPE) responses as internal load indicators while performing duet routines during training and competition, both in the technical and free programs of synchronized swimming (SS). Participants were ten SS Olympic medalists (age: 17.4 ± 3.0 years, height: 164.0 ± 6.1 cm, body mass: 52.0 ± 6.4 kg, training: 36.3 ± 6.2 $h \cdot week^{-1}$, experience: 9.2 ± 2.6 years). They were monitored while performing the same technical duet (TD) or free duet (FD), during a training session (T) and during an official competition (C). HR was continuously monitored. RPE was assessed using the Borg CR10 scale. HR responses during T and C were almost identical: pre-exercise mean HR ($beats \cdot min^{-1}$) was 130.5 ± 13.9 (T) and 133.6 ± 7.7 (C), and quickly increased yielding mean peak values of 184.8 ± 5.8 (T) and 184.8 ± 6.6 (C), with interspersed bradycardic events down to 86.6 ± 4 (T) and 86.3 ± 5 (C). Routines were perceived as “hard” to “extremely hard” by the swimmers in both conditions, and mean RPE scores (0-10+) were equally high during C (7.9 ± 1.2) and T (7.5 ± 1.2) (P=0.223). RPE inversely correlated with minimum (R=-0.545; P=0.008) and mean HR (R=-0.452; P=0.026), and positively correlated with HR range (R=0.520; P=0.011). The internal load imposed by SS duets performed during training is virtually identical to that elicited in a real competitive situation. Therefore, practicing competitive routines is suitable for developing and maintaining the cardiovascular fitness that is needed for specific conditioning in elite synchronized swimmers, with the added value of favoring exercise automaticity, inter-individual coordination, and artistic expression simultaneously.

Keywords: synchronized swimming, heart rate, rating of perceived exertion, RPE, training, competition.

INTRODUCTION

Synchronized swimming (SS) has been an event at the Summer Olympics since the 1984 Games. The current Olympic program has competition in duet and team events and includes free and technical routines. Successful performance depends on the swimmers' ability to execute a synchronized routine of elaborate moves in the water accompanied by music. To attain this goal, synchronized swimmers must train for aerobic and anaerobic fitness, strength, power, endurance, flexibility, performance skill and artistic expression (34). As a result, training demands at an elite absolute level often result in high-volume (averaging about 40 $h \cdot week^{-1}$) (35, 40), high-intensity training programs (35), including long periods devoted to choreography when much time is spent in the pool to perfect synchronization. The regulation of exercise intensity during SS training is critical to the success of each conditioning program since exercise intensity set too low does not induce the desired physiological adaptations while an exercise intensity set too high may result in overtraining fatigue or injuries from overuse in this kind of athletes (34, 35, 54). For this reason, balancing the training components listed previously to produce the desired result at the time of competition without producing overuse injuries should be the major task for all National Team coaches (35). In this line, to monitor and control the training process, it is important to have a valid measure of the swimmers' internal training load (12). This is particularly relevant in this kind of aesthetic sports, where the planned external load is often different for each team member because of the variety of elements configuring each routine as well as the order in which they are executed.

The use of telemetric heart rate (HR) monitors provides a simple, non-invasive, and convenient method for a continued assessment of cardiovascular load and is widely used to assess exercise intensity (1), however there is limited information available on the physiological stress generated during SS routines (25). This is partly because of the challenges of measuring physiological parameters in the pool, especially considering that up to 50% of exercise time is spent underwater (16). Based on HR response both in free and technical programs, previous reports point out that the intensity of routine exercises is high both during training (19, 38) and competition (40). However, the most unique feature of SS is the long time spent holding breath while performing several movements combining isometric and intense dynamic exercise (25, 40). A recent study from our group reported average HR peak values of 191.7 ± 8.7 bpm, with interspersed bradycardic events down to 88.8 ± 28.5 bpm, and an average HR range of 103.5 ± 28.7 bpm during the execution of all the competitive routines (40). While apnea and facial immersion increase the parasympathetic tone causing HR reduction (23, 42), exercise enhances the sympathetic stimulation of the heart (19) and increases HR. Thus, when the swimmer starts holding breath during the routines, both inputs compete with each other to control the HR (53), but the diving response is powerful enough to override the intense HR chronotropic stimulation producing a rapid development of hypercapnia and hypoxia (15).

Different from training, competition is a challenging situation which usually stimulates higher psycho-physiological responses in the participant (50). Research in this field suggests that stress due to competition is added to the physiological stress caused by exertion, which in itself is capable of affecting hormone secretion (18, 50) and autonomic nervous system activity (7) producing changes in many of the athletes' cardiovascular parameters (e.g. increasing HR) (6, 32). In addition, competitive performance is affected by decision-making and psychological aspects to a greater extent, since there are opponents and the result is of greater importance. Prior mental fatigue and anxiety induced by a challenging competitive event would elevate the RPE throughout exercise and hasten exhaustion (20, 26). However, motivation, a higher degree of self-efficacy or the willingness to exert effort may counteract any negative influence of higher a RPE (20, 55). In this context, the feeling of fatigue depends partly upon on the interpretation of physical sensations. The feeling of fatigue is dependent, therefore, on the individual's unique interpretation of his or her experience. Borg category rating of perceived exertion (RPE) scales based on subjective feelings of exertion and fatigue can be used to both prescribe and regulate exercise intensity. Previous investigations have proven that RPE scales are a useful tool to quantify exercise intensity based on its relationship with physiological criterion measures such as HR, blood lactate concentration, oxygen uptake and minute ventilation (8). Additionally, previous work supports the validity, reliability and the practical application of the RPE scales to quantify exercise intensity in aquatic disciplines such as swimming (14, 39, 51), and acrobatic diving (31). Recently, a significant relationship between RPE scores and salivary cortisol ($r=0.64$, $p<0.005$) has been found when tested at a daily pool training session in a SS duet (49). This experimental evidence seems a sensible approach considering the use of RPE for controlling the intensity in SS. Moreover, some features of this scale, such as its noninvasive, and easy administration in field contexts and that not specialized staff is required, may favor its use to indicate the intensity accurately avoiding the expensive use of telemetric HR monitors.

Attending the demands of the training schedule and the risk of injuries related to overuse in elite SS, it is very important to monitor and control athletes' internal load to ensure that each swimmer receives adequate training stimulus. A straightforward approach is to compare the response of athletes in training sessions with those in real competition in order to ascertain whether swimmers may achieve the competitive intensity during training sessions. Provided that limitations imposed by SS competition can be overcome, HR (an objective physiological marker) and RPE (a subjective perceptual marker) may provide a valid insight.

Taking into account all the above-mentioned considerations, the purpose of this study was to investigate and compare the internal load imposed by duet routines performed during training and competition by means of HR and RPE monitoring in elite synchronized swimmers. We hypothesized that the competitive situation would simultaneously alter the heart rate response and the RPE assessment in elite synchronized swimmers. Additionally, we also aimed at determining whether there is a relationship between both types of assessment. Based on recent research (33), we hypothesized that the pattern of interaction between the physical load (as reflected by the HR response) and the perception of effort during competition would vary due to the stress of competition.

METHODS

Subjects

Ten elite synchronized swimmers volunteered to participate in the study. Seven were juniors (J, 15-18 years) and three were seniors (S, >18 years), though they were competing at the National championships at the highest level and were not classified according to their age category. Their age, physical characteristics, training and competitive experience, and performance level are summarized in table 1. All of them were medalists in the London 2012 Summer Olympic Games during the time of the study eight in the free team and two also in the free duet. This study was approved by the Ethics Committee for Clinical Sport Research of Catalonia, and each subject subsequently signed an informed consent document before participation.

---Table 1 near here---

Procedures

The study protocol is shown in figure 1. Swimmers performed the same competitive technical duet (TD) or free duet (FD) routines on two different occasions, during a training session (T) and during an official competition (C) by an interval of 48 to 72 h. Both routines were executed in the morning at about the same time of day (± 2 h), and allegedly at similar points in their ovarian cycles to minimize the difference caused by the effect of biological rhythms (52) and changes in performance ability. The TD routine is composed of eight required elements in a predetermined order and lasts 2:20 min:s. The FD routine allows more flexibility to demonstrate interpretation of the music and skill and lasts about 3:30 min:s (11). Data collection took place in February, during the third microcycle of the competition period. All subjects ingested a similar nutrient intake on both occasions and were allowed to drink water at libitum before each testing session Because both ambient and water temperature may influence diving bradycardia in humans, which in turn may affect the HR response (43), both sessions took place at similar water (25–26 ºC) and air temperature (26-27 ºC) in a 50-m indoor pool (with 30 m available for use).

---Figure 1 near here---

Before the chosen T, the participants' height and body mass were measured according to the ISAK standard protocol (International Standards for Anthropometric Assessment, 2006). Body mass was measured to the nearest 0.1 kg using an electronic scale (Seca Instruments Ltd., Hamburg, Germany). Height was measured to the nearest 0.1 cm using a stadiometer (Holtain Ltd., Crymych, United Kingdom). After a 30-min standardized warm-up including swimming, figures, and monitored routine exercises followed by a full passive recovery period, participants completed the same TD or FD routine with the same partner as in the approaching championships. Swimmers were informed of the aim of the study and were encouraged to perform at their best.

For the official competition session (C), measurements were taken during the 2011 Spanish National Winter Championships, qualifying event for the recruitment of the team members representing Spain in the London 2012 Summer Olympic Games. The standardized 30 min warm-up was completed within their scheduled time frame before competition. The same duet routines (TD or FD) were performed in the official indoor pool. Official judges assessed and marked each routine according to FINA rules (11).

Heart rate monitoring

HR was measured using waterproof beat-by-beat HR monitors (CardioSwim, Freelap, Fleurier, Switzerland). The belt strap contains two chest electrodes wired to a monitoring device that can be downloaded onto a computer after the recording. Portable beacon transmitters (Tx H_2O, Freelap, Fleurier, Switzerland) were placed by the pool at different locations so that the HR monitors' microprocessor units could recall specific times and positions during the competition. To minimize potential instrumentation bias, swimmers wore the HR monitors during training sessions within one 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 1-min average recorded after the specific warm-up and a 5-min recovery period, immediately before the start of the routine; HR_{peak} and HR_{min} are the highest and lowest 1-s value during the exercise, and HR_{mean} is the arithmetic mean for the entire exercise. Post-exercise HR are the average at minutes 1, 3, and 5 (HR_{post1}, HR_{post3}, HR_{post5}).

Rate of perceived exertion

The Borg CR10 category-ratio scale (4) was selected to rate the perceived intensity of exertion (Figure 2). A graphical, colored, verbal-anchored scale was shown to the swimmers shortly after the routine as they were standing on the edge of the pool waiting for marks. The week before competition, all participants were assessed repeatedly during at least three training sessions so as to disclose learning effects and to improve the consistency of the measurements during competition.

---Figure 2 near here---

Statistical analysis

Mean and standard deviation were calculated for each dependent variable. Once the data were tested for normality (Shapiro-Wilks test), paired *t*-tests were used to evaluate differences between T and C routines for each HR and RPE parameter. Pearson interclass product-moment correlations (*R*) were used to examine the relationship between HR and RPE variables. Precise *P* values are reported and $P<0.05$ was considered significant.

RESULTS

Heart rate response

Figure 3 illustrates the HR profiles corresponding to one of the participants before, during, and after two FD routines performed during T and C. An almost identical pattern was observed, in where HR, after a period of intense anticipatory pre-activation, quickly increases to 181.2 and 176.8 bpm, interspersed with periods of marked HR decrease down to 71.1 and 50.8 bpm, respectively. The variable names referred to in the text, tables, and figures are shown graphically.

---Figure 3 near here---

Table 2 shows the individual and group values for HR before, during, and after the duet routines, as well as post-exercise RPE, in both T and C conditions. There were no significant differences in any of the HR parameters recorded in either condition. No differences were observed between routine types (TD vs. FD) either.

---Table 2 near here---

Rate of perceived exertion

Mean RPE scores (table 2) corresponded to the “hard” to “extremely hard” verbal anchored levels, and differences observed between C (7.9 ± 1.2) and T (7.5 ± 1.2) scores were not significant. No differences were observed between routines (TD vs. FD).

Relationship among variables

Table 2 (bottom) shows the interclass correlation between T and C values for all parameters. The correlation coefficient was highest for HR_{range} (R=0.97, P<0.001), followed by HR_{min} (R=0.95, P<0.001) (Figure 4), HR_{mean} (R=0.80, P=0.006), and lowest for HR_{pre} (R=0.65, P=0.044). HR_{peak} correlation closely approached statistical significance (R=0.058, P=0.058). Recovery HR ($HR_{post1,3,5}$) in both conditions were not significantly correlated.

---Figure 4 near here---

RPE during competition was also significantly correlated with RPE during training (R=0.67, P=0.034). RPE was inversely correlated with HR_{min} (R=-0.545; P=0.008) and HR_{mean} (R=-0.452; P=0.026), and positively correlated with HR_{range} (R=0.520; P=0.011) (Figure 5).

---Figure 5 near here---

DISCUSSION

The major finding of this study was that the internal load imposed by duet routines performed during training assessed by means of objective (HR) and subjective (RPE) markers, and the pattern of interaction between both indicators, were virtually the same as in a real competitive situation among elite synchronized swimmers. Additionally, the findings showed that RPE scores were inversely related to the minimum and mean HR levels, and positively related to the range of HR variation during exercise, whereas they did not relate to the peak or recovery HR. This strongly suggests a positive relationship between the perceived intensity of exertion and the duration and / or frequency of bradycardic events during the routines and not unrelated to competitive stress condition.

Heart rate response

In this study during the execution of the duets, cardiovascular demands were equally high in both T and C conditions, with HR quickly approaching maximal levels (184.8 ± 5.8 and 184.8 ± 6.6 bpm, respectively), and interspersed periods of marked bradycardia during the intense exercise bouts performed in apnea (109.1 ± 17.1 and 109.4 ±28.0 bpm), all of which resulted in a wide HR range (75.8 ± 7.4 and 75.3 ± 28.9 bpm), confirming earlier observations (38, 40). These results are consistent with reports on the presence of human diving bradycardia triggered by apnea in synchronized swimmers (2, 13, 17, 19, 38, 40). It is well documented that immersions of the swimmers' head, with the concomitant apnea and stimulation of the cold-receptors of the upper part of the face, elicits the diving response (43). This is characterized by selective vasoconstriction and heart rate reduction (bradycardia) is the magnitudes of which are often used to estimate the overall magnitude of the response (9, 23). Blood flow has been shown to be derived away from organs that can function anaerobically, but is maintained to organs sensitive to asphyxia such as the heart and brain and to any hard working muscles (41). The general differences in magnitude of bradycardia among the studies referenced above, may be explained by the pattern of response to different exercise' intensities as well as by the duration of the breath holding (BH) periods according to performed exercise, e.g. execution of complete routines, set of figures or static positions underwater.

The absence of differences between T and C in the anticipatory HR pre-activation rates suggests that the alteration of HR dynamics in elite synchronized swimmers before execution is probably due to the simultaneous sympathetic activation and parasympathetic withdrawal necessary to ensure anticipatory metabolic and cardiovascular responses to a physical effort (10), and not because of mental stress and anxiety due to competition proximity, as has been suggested by several authors (24, 28). Automaticity suggests non-conscious attention to the act itself while in execution, and unaware of and therefore vulnerability to external and internal distractors (46). Although stress has been found to have a detrimental effect on performance disrupting automaticity (27), our data suggest that elite synchronized swimmers are able to self-regulate competitive anxiety, possibly through regulating expectations, confidence, and attention prior to and/or during performance (46). This is likely to be due to their experience and/or specific training. Performance limitations have been consistently reported as a consequence of self-focused (internal) attention (22, 30). Accordingly, our results suggest that external focus facilitates automatic control processes to regulate the movements associated with the optimal performance characteristic of elite athletes (56). Therefore, elite synchronized swimmers would be highly motivated in both conditions because of repetitive practice of the duets during training, relieving them of the attentional demands other athletes face. Thus, it seems reasonable to hypothesize that the attainment of a higher skill level –typically in elite swimmers– would be associated with a greater automaticity in performing motor acts and a lower metabolic energy cost for achieving the task goal, with the consequent reduction of attentional demands and favoring the use of an energy-efficient preferred mode (21, 46, 47), which in turn would imply a similar HR pre-activation response in both conditions.

The similarity in the HR parameters during the execution in both experimental situations can be analyzed in terms of 1) the specific influence of the diving response during BH periods; 2) the automaticity of movements; and 3) the specific training adaptations. First, the similar diving response can be explained by the close correspondence in the time and duration frame of the frequent and often long BH periods in both conditions (Figure 3). Second, it should be highlight that both exercises were identical in composition and timing. SS rules demand a stable and standardized environment as well as required mandatory elements for the technical programs and time limit (2:20 min:s for TD, and 3:30 min:s for FD) (11). These prescriptions fix the time frame and content characteristics and avoid the uncertainty that occurs in other sport performances. In addition, although it is well established that variation in HR over time reflects the individuals' ability to adapt to internal and external demands (36), the lack of uncertainty in both conditions and the automaticity of the actions because of practice suggests non-conscious attention to the act itself while executing, and unawareness of and vulnerability to external and internal distractors (46). Third, synchronization with music and between couples requires many hours of repetition during training sessions (about 40 h·week^{-1} at the elite level) (40) for the acquisition of sport-specific skills (35). In duets in particular, swimmers generate motor patterns that require constant micro-adjustments to synchronize to the tenth of a second, and therefore continuous programmed anticipations. This skilled motor performance requires the ability to complete the task with minimum energy expenditure. Continuous practice during training reduces the metabolic energy cost of performance while practice-related refinements to coordination and control are also associated with significant reductions in muscle activation (21). It follows that, due to practice, elite swimmers would be able to execute their routines with a constant mechanical power output in both conditions, leading to a reduction in their HR and metabolic energy expenditure (48). Similar to these findings, Semin et al. (2008) (45) and Viru et al. (2009) (50) observed that endurance trained athletes attained similar mean HR responses between training and competitive sessions. In contrast, several investigations on taekwondo practitioners (6), basketball players (32) and long distance runners (44) found that mean HR was higher in competition than during training. The remarkably high cardiovascular demands during the routine execution, either in training (38) and competition (40) as well as the fact that SS is a routine-based sport, could explain differences between previous research and the current findings.

Association between RPE and HR response

The second aim of the study was to examine the association between RPE and HR, and to identify patterns of interaction between stress perception and internal load in SS competition. In this study, the RPE score was inversely related to HR_{min} and HR_{mean}, and positively related HR_{range} during exercise (Figure 5), while it was related to HR_{peak}, or recovery HR. This strongly suggests a relationship between the perceived intensity of exertion and the magnitude and / or frequency of bradycardic events during the routines, and would certainly reflect the psycho-physical stress imposed by repeated and/or prolonged BH periods.

The inputs for RPE can be categorized into those of central and peripheral origin (37). Based on the reasoning discussed before (HR response), we hypothesize that the perceptions primarily associated with the cardiorespiratory system resulting from tachycardia, tachypnea, and dyspnea (57) might have provided more powerful stimuli for perceived effort changes than peripheral effort perceptions (i.e. for arms and legs), given the nature of the routines in which swimmers tend to spend 50% of the routine underwater (16). Moreover, the cardiovascular responses to apnea during dynamic exercise occur also during the recovery period (15), which might have decreased the perceived exertion of swimmers, leading them to lower scores. Moreover, previous research has found RPE scores to be moderately correlated with HR (weighted mean

R=0.62), even in modes of exercise that are progressive or intermittent (e.g., running, walking or swimming), where perception could be expected to more readily reflect exertion (8). In any case, inconsistencies concerning the association between RPE and HR have appeared in the literature since Borg (3, 5) tried to validate his RPE scale against HR.

PRACTICAL APPLICATIONS

Improved understanding of internal load in sports training and competition, and how to use simple markers to monitor it, can be useful for training purposes. Coaches should be aware that the quantification of internal load during T and C is necessary to analyze the periodization of training (29). In SS, some coaches and athletes believe that "the more, the better" and would exceed the appropriate training load for optimal adaptation (54). Therefore, monitoring the internal load during training and competition might help coaches to plan appropriate loads maximizing recovery and performance. Our finding that the execution of practice and competitive routines is equally demanding is of considerable relevance for elite coaches to regulate the training load, both for fitness and technical improvement. These results confirm that executing the routine repeatedly, in whole or in part, during training workouts is a very specific method for reproducing the physiological demands of competition. Furthermore, practicing simulated routines with the same challenging technical content in a training environment would seem to be a more feasible approach if the cardiovascular responses or adaptations are to be assessed as part of a training monitoring procedure. This type of practice has the added value of favoring exercise automaticity, inter-individual coordination, and artistic expression simultaneously. Thus, complete and fractioned routine practice (including BH periods) should be considered a highly specific type of training overload because of the swimmer's exposure to greater psycho-physical stress as compared to less specific training modes.

As the routine use of HR-based methods to systematically monitor internal load is not always feasible during both training and competitive sessions in SS, the use of the RPE method seems to be a good alternative strategy for coaches to quantify internal load as this provides a cost-efficient, noninvasive, and reliable method for quantifying the internal load. Based on our results and the literature reviewed, RPE might help to control the internal load during training so as to design appropriate and balanced training programs and to optimize competitive routines, closely matched to swimmers' level of fitness and skill. Moreover, when the aim is to plan training sessions that mimic competition demands, it would be advisable to accurately monitor training loads taking into account the similarity between T and C. Utilizing repeated RPE assessments may also allow coaches to monitor the training response and adaptation in swimmers and to verify periodization strategies (12). However, the moderate correlations reported do not support this method as a valid substitute of HR-based monitoring. It should be taken into account how different factors (e.g. exercise intensity, apnea, and autonomous neural control) contribute to perceived exertion in SS performance. Thus, this simple method has the potential to become a valuable tool for coaches, but practice is necessary to get valid information from this internal load quantification strategy. To summarize, monitoring internal load using HR and / or RPE in SS can help coaches to control the intensity of exercise over time with the intent to minimize boredom, prevent overtraining, and reduce injuries (29) and, thus, to optimize different aspects of the training load.

CONCLUSIONS

This study shows that the internal load imposed by duet routines performed during training is virtually identical to that elicited in a real competitive situation among elite synchronized swimmers. Results strongly suggest a positive relationship between the perceived intensity of exertion and the duration and / or frequency of bradycardic events during routines. These findings can be explained by the effects of automaticity–embodied through the replication of the same movement sequence in practice–, and by the swimmers' long-term adaptations to specific routine exercise and apnea. These findings can help coaches to optimize the contents, sequence, and pacing of competitive routines in accordance with the physiological characteristics of athletes.

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FIGURES LEGENDS

Figure 1. Study protocol. T, Training session; C, Competition event; TCS, total competitive score; RPE, rating of perceive exertion; HR, heart rate monitoring

Figure 2. The Borg CR10 scale (Borg, 1982, 1998, 2003)

Figure 3. Heart rate profiles before, during (shadowed), and after a free duet routine performed during training (dotted line) and competition (solid line) in one of the swimmers. Line depicts smoothed 5-s averaged values for clarity

Figure 4. Correlation between heart rate parameters during duet routines performed during training and competition in elite synchronized swimmers (*n*=10): (A) mean (HR_{mean}), (B) minimum (HR_{min}), and (C) range (HR_{range}) heart rate. Regression (solid) and identity (dotted) lines are depicted, and regression equations and determination coefficients (R^2) shown.

Figure 5. Correlation between the rate of perceived exertion (RPE) and heart rate parameters during duet routines in an official competition in elite synchronized swimmers (*n*=10): RPE *vs.* (A) mean (HR_{mean}), (B) minimum (HR_{min}), and (C) range (HR_{range}) heart rate. Regression (solid) and identity (dotted) lines are depicted, and regression equations and determination coefficients (R^2) shown.

Table 1. Physical characteristics of the subjects

Subject	Age (years)	Body Height (cm)	Body Mass (kg)	BMI ($kg\cdot cm^{-2}$)	Training ($h\cdot week^{-1}$)	Experience (years)	TCS (points)
1	15	161	51	19.7	33.0	9	76.7
2	24	163	47	17.7	44.0	6	78.4
3	16	160	43	16.8	35.0	9	82.6
4	21	171	54	18.5	45.0	15	85.9
5	15	168	57	20.2	31.0	8	82.6
6	17	158	51	20.4	30.0	6	76.6
7	15	173	64	21.4	30.0	9	76.7
8	17	169	58	20.3	42.0	11	79.7
9	18	154	45	19.0	42.0	9	81.8
10	16	163	50	18.8	31.0	10	75.4
Mean ± SD	17.4 ± 3.0	164.0 ± 6.1	52.0 ± 6.4	19.3 ± 1.4	36.3 ± 6.2	9.2 ± 2.6	79.6 ± 3.4

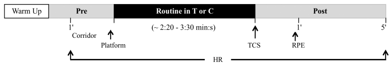
BMI, body mass index; TCS, total competition score (present National championships)

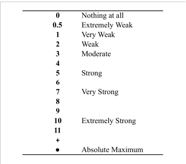
Table 2. Heart rate parameters before (PRE), during (ROUTINE), and after (POST) duet routines, and RPE, in training and competition

		PRE		ROUTINE										POST							
		HR_{pre}		HR_{mean}		HR_{mean} †		HR_{peak}		HR_{min}		HR_{range}		HR_{post1}		HR_{post3}		HR_{post5}		RPE #	
Subject	Routine	T	C	T	C	T	C	T	C	T	C	T	C	T	C	T	C	T	C	T	C
1	FD	113.2	122.8	159.8	165.7	91.1	94.4	171.8	175.5	123.8	143.9	48.0	31.6	163.4	167.0	143.8	148.9	127.5	133.9	8	8
2	TD	132.5	124.7	167.5	156.0	90.4	84.1	185.4	176.0	129.0	127.0	56.0	49.0	168.9	164.4	150.0	139.0	140.2	124.3	5	7
3	FD	122.1	131.4	164.6	164.8	86.7	86.8	187.5	189.8	112.0	109.8	75.5	80.0	166.2	176.1	144.2	164.7	130.7	144.4	9	9
4	TD	110.8	134.9	158.7	159.6	82.8	83.3	185.1	191.6	112.0	117.0	73.4	74.1	151.4	157.3	125.3	134.5	115.4	118.8	8	8
5	FD	153.4	140.8	150.3	137.8	83.0	76.1	181.2	176.8	71.1	50.8	110.0	125.9	161.6	144.3	136.3	140.7	125.2	127.6	8	10
6	FD	135.3	141.0	169.3	171.9	87.9	89.3	186.9	192.6	103.5	110.9	83.4	81.6	164.6	168.7	133.7	144.6	116.7	127.3	8	7
7	FD	135.0	134.7	151.2	154.8	82.2	84.2	182.8	183.9	98.6	91.5	84.1	92.4	172.6	151.7	153.6	150.9	142.7	141.5	7	7
8	TD	140.3	133.0	173.3	171.2	89.1	88.0	194.5	187.1	123.0	123.0	72.0	64.0	181.9	172.4	158.2	154.9	147.3	139.1	8	8
9	TD	118.7	126.3	172.8	173.8	92.5	93.1	186.7	185.0	120.0	138.0	67.0	47.0	171.2	169.2	145.4	145.7	137.1	128.0	6	6
10	FD	144.0	146.7	152.8	158.6	80.6	83.7	186.7	189.5	98.1	81.8	88.5	107.7	163.8	157.7	139.7	147.9	122.8	136.1	8	9
Mean		130.5	133.6	162.0	161.4	86.6	86.3	184.8	184.8	109.1	109.4	75.8	75.3	166.6	162.9	143.0	147.2	130.6	132.1	7.5	7.9
SD		13.9	7.7	8.7	10.7	4.0	5.0	5.8	6.6	17.1	28.0	7.4	28.9	8.0	9.9	9.8	8.6	11.0	8.2	1.2	1.2
Differences T-C		3.1		0.6		0.3		0.0		0.3		0.5		3.7		4.2		0.5		0.4	
t (*P*-value)		0.905 (0.389)		-0.293 (0.78)		0.293 (0.78)		-0.055 (0.96)		0.062 (0.96)		-0.116 (0.91)		-1.154 (0.28)		1.493 (0.17)		0.486 (0.64)		-1.309 (0.22)	
Correlation T-C																					
R (*P*-value)		0.65 (0.044)		0.80 (0.006)		0.74 (0.014)		0.62 (0.058)		0.95 (<0.0001)		0.97 (<0.0001)		0.38 (0.277)		0.54 (0.106)		0.48 (0.162)		0.67 (0.034)	

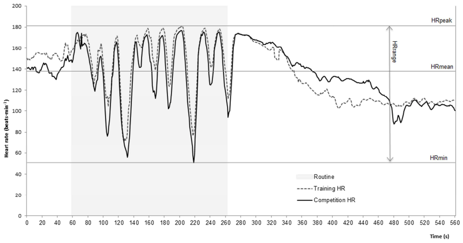
T, training; C, competition. HR_{pre}, last min before routine; HR_{peak}, $HR_{mean,}$ HR_{min}, HR_{range}: peak, mean, minimum, and range values during routine; HR_{post1}, HR_{post3}, HR_{post5}: 1st, 3rd, 5th min during recovery.

† Expressed as % of HR_{peak}; # RPE 0-10 score

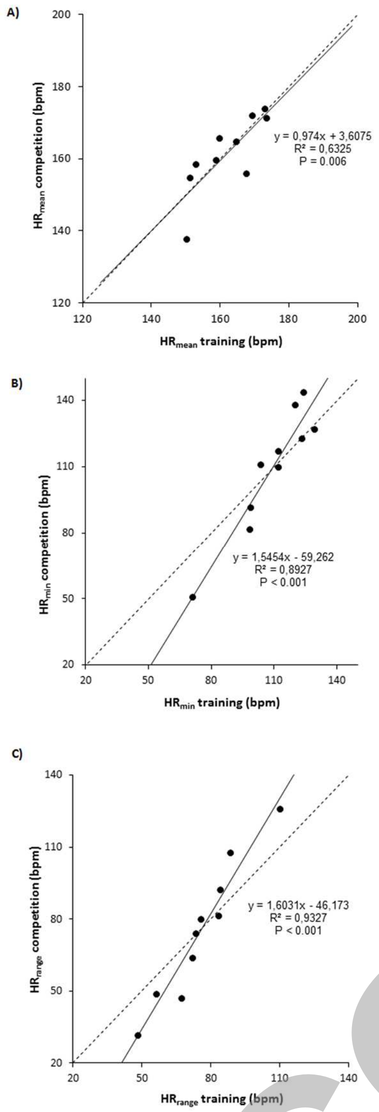

Warm Up
Pre
Routine in T or C
Post
1'
Corridor
Platform
(~ 2:20 - 3:30 min:s)
TCS
1'
RPE
5'
HR



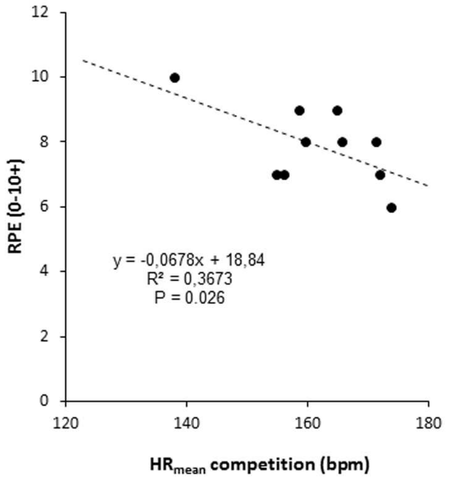
0	Nothing at all
0.5	Extremely Weak
1	Very Weak
2	Weak
3	Moderate
4	
5	Strong
6	
7	Very Strong
8	
9	
10	Extremely Strong
11	
+	
●	Absolute Maximum



Heart rate (beats·min⁻¹)
200
180
160
140
120
100
80
60
40
20
0
HRpeak
HRrange
HRmean
HRmin
Routine
Training HR
Competition HR
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
520
540
560
Time (s)

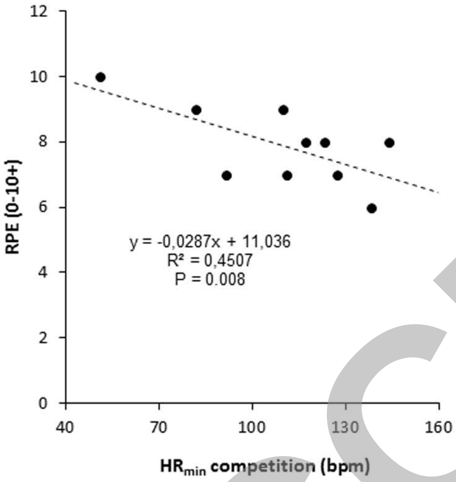

A)
HR$_{mean}$ competition (bpm)
200
180
160
140
120
120
140
160
180
200
HR$_{mean}$ training (bpm)
y = 0,974x + 3,6075
R² = 0,6325
P = 0.006
B)
HR$_{min}$ competition (bpm)
140
110
80
50
20
20
50
80
110
140
HR$_{min}$ training (bpm)
y = 1,5454x - 59,262
R² = 0,8927
P < 0.001
C)
HR$_{range}$ competition (bpm)
140
110
80
50
20
20
50
80
110
140
HR$_{range}$ training (bpm)
y = 1,6031x - 46,173
R² = 0,9327
P < 0.001

A)



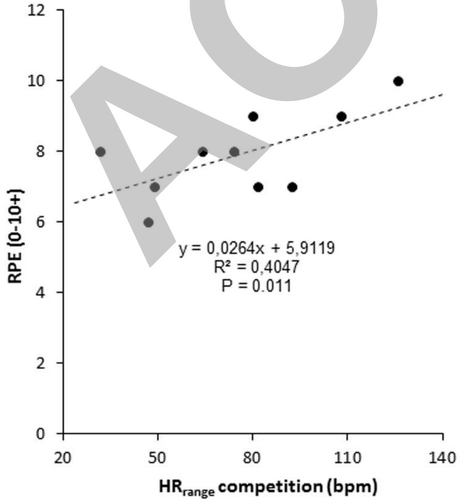
12
10
8
6
4
2
0
RPE (0-10+)
y = -0,0678x + 18,84
R² = 0,3673
P = 0.026
120
140
160
180
HRmean competition (bpm)

B)



12
10
8
6
4
2
0
RPE (0-10+)
y = -0,0287x + 11,036
R² = 0,4507
P = 0.008
40
70
100
130
160
HRmin competition (bpm)

C)



12
10
8
6
4
2
0
RPE (0-10+)
y = 0,0264x + 5,9119
R² = 0,4047
P = 0.011
20
50
80
110
140
HRrange competition (bpm)

PAPER III

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

Authors
L. Rodríguez-Zamora[1], X. Iglesias[1], A. Barrero[1], D. Chaverri[1], A. Irurtia[1], P. Erola[2], F. A. Rodríguez[1]

Affiliations
[1] Institut Nacional d'Educació Física de Catalunya (INEFC), INEFC-Barcelona Sports Science Research Group, Universitat de Barcelona, Spain
[2] Department of Computer Engineering and Mathematics, Universitat Rovira i Virgili, Tarragona, Spain

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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Bibliography
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Correspondence
Dr. Xavier Iglesias
Institut Nacional d'Educació Física de Catalunya (INEFC)
Universitat de Barcelona
INEFC-Barcelona Sports Sciences Research Group
Av. de l'estadi 12–22
Barcelona 08038
Spain
Tel.: +34/60/9386 571
Fax: +34/93/4260 751
xiglesias@gmail.com

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 ($h \cdot week^{-1}$)	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-

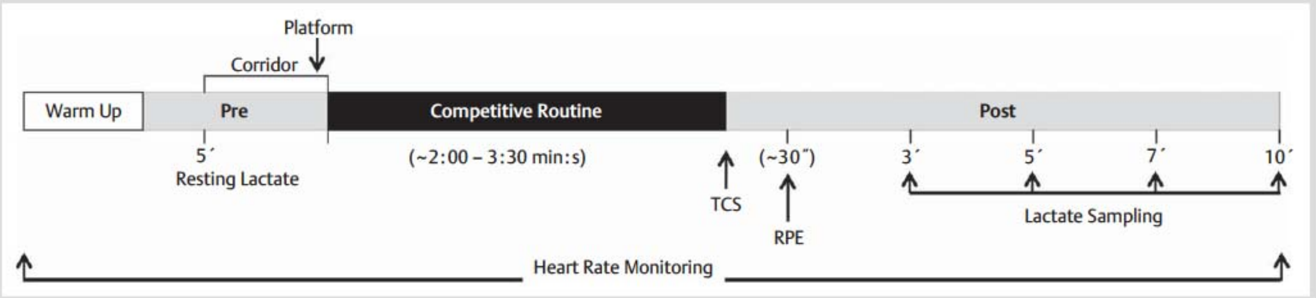

Fig. 1 Study protocol TCS: total competition score; RPE: rating of perceived exertion; Corridor and platform: swimmers' location at the pool.

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

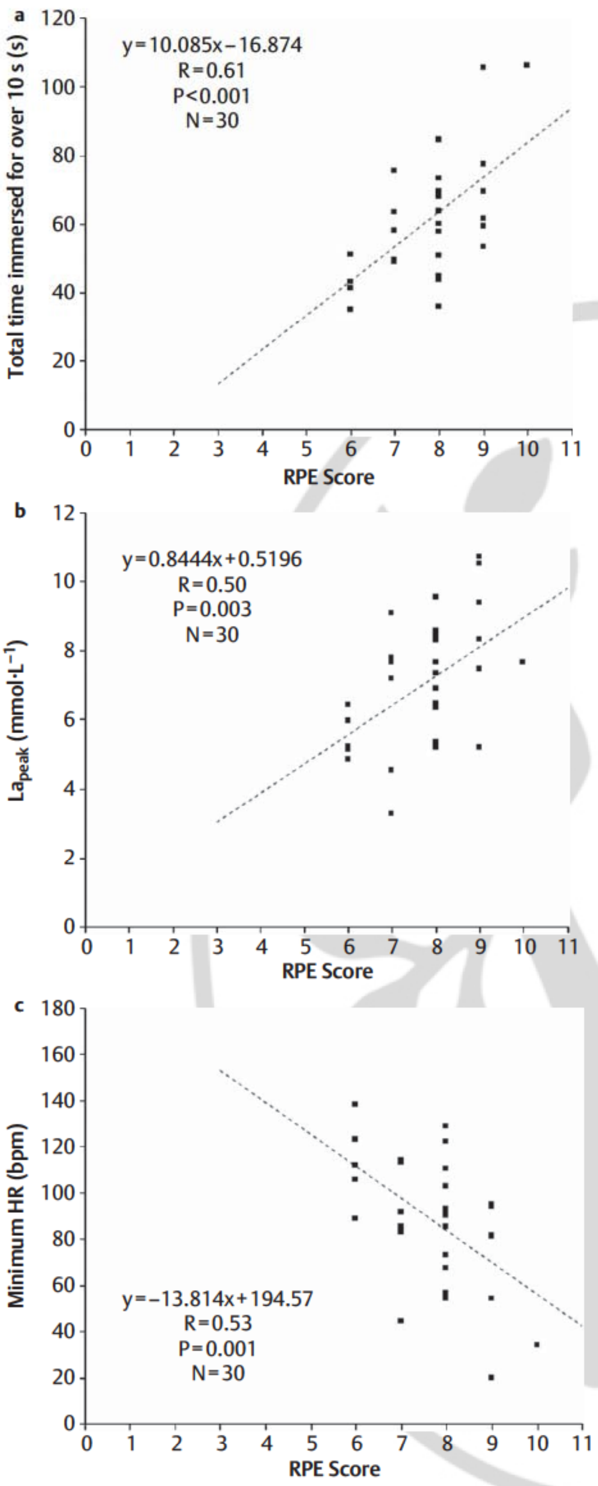

Fig. 2 Linear Regression Regression analysis between RPE scores and **a** total time immersed for longer than 10 s ($TIM > 10 s$) during the routine, **b** peak post-exercise lactate concentration (La_{peak}) and **c** minimum heart rate during the routine (HR_{min}). Linear regression equations and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

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

($R = 0.50$, $P = 0.003$) 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:

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

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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