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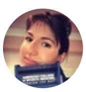

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Research Article

Blood lactate accumulation during competitive freediving and synchronized swimming

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ABSTRACT

A number of competitive water sports are performed while breath-holding (apnea). Such performances put large demands on the anaerobic system, but the study of lactate accumulation in apneic sports is limited. We therefore aimed to determine and compare the net lactate accumulation (NLA) during competition events in six disciplines of competitive freediving (FD) and three disciplines of synchronized swimming (SSW).

The FD disciplines were:

- static apnea (STA; n = 14)
- dynamic apnea (DYN; n = 19)
- dynamic apnea no fins (DNF; n = 16)
- constant weight (CWT; n = 12)
- constant weight no fins (CNF; n = 8)
- free immersion (FIM; n =10)

The SSW disciplines were solo (n = 21), duet (n = 31) and team (n = 34). Capillary blood lactate concentration was measured before and three minutes after competition performances, and apneic duration and performance variables were recorded.

In all nine disciplines NLA was observed. The highest mean (SD) NLA (mmol•L^{-1}) was found in CNF at 6.3 (2.2), followed by CWT at 5.9 (2.3) and SSW solo at 5 (1.9). STA showed the lowest NLA 0.7 (0.7) mmol•L^{-1} compared to all other disciplines ($P < 0.001$). The NLA recorded shows that sports involving apnea involve high levels of anaerobic activity. The highest NLA was related to both work done by large muscle groups and long apneic periods, suggesting that NLA is influenced by both the type of work and apnea duration, with lower NLA in SSW due to shorter apneic episodes with intermittent breathing.

INTRODUCTION

Several popular underwater sports exist which involve athletic performance during breath-holding, including competitive freediving (FD), synchronized swimming (SSW), and team sports such as underwater rugby and hockey. These sports are likely to involve high levels of both aerobic and anaerobic metabolic activity [1,2], but the extent of the involvement of the anaerobic system has received limited scientific study. Human apneic diving capacity, as well as that of other mammalian divers, is determined by the total aerobic and anaerobic metabolic stores, the asphyxia tolerance, and the rate at which the resources are used, i.e., metabolic rate [3]. While the aerobic store is usually considered to be the major determinant of breath-hold diving ability, anaerobic resources clearly affect the maximal diving capacity of a species [4].

During voluntary apnea, oxygen (O_2) is mobilized from finite stores in the lungs, blood and other tissues, while the cardiovascular diving response restricts blood flow to selected regions and reduces heart rate and cardiac output [5,6]. At the same time, the arterial tension of carbon dioxide ($PaCO_2$) increases until a certain point that causes a stimulation of respiration, which overrides the voluntary inhibition and restarts breathing [7]. During resting apnea, blood flow is directed mainly toward the brain and heart, while the rest of the organism receives a limited blood flow [5,6]. The restricted blood flow in some tissues can lead to lactate accumulation. O_2-preserving mechanisms result in a low metabolic rate, which can postpone the so-

KEYWORDS: apnea; anaerobic; breath-hold diving; exercise; hypoxia; underwater; sports

TABLE 1. Characteristics of studied competition disciplines and number of subjects in the current study

discipline		goal	characteristics	muscles involved* lower body	muscles involved* upper body	sample size
static apnea (STA)		maximal duration	resting apnea			14
dynamic apnea (DYN)		maximal distance	horizontal swimming w/fin	X		19
dynamic apnea no fins (DNF)			horizontal swimming w/o fin	X	X	16
constant weight (CWT)		maximal depth	vertical swimming w/fin	X		12
constant weight no fins (CNF)		maximal depth	vertical swimming w/o fin	X	X	8
free immersion (FIM)		maximal depth	pulling with arms down and up on a line		X	10
synchronized swimming:	solo	performance score	intense dynamic apneic	X	X	21
	duet	performance score	exercise with short	X	X	31
	team	performance score	eupneic periods	X	X	34

* X indicates major muscle groups involved

called "breaking point" of apnea and point to hypoxic loss of consciousness [8,9]. During apneic exercise, working muscles will also receive part of the blood flow, but when stores (i.e., reduced O_2 content) have been depleted they rely mainly on anaerobic metabolism, with concurrent accumulation of lactate [2,9,10]. Lactate is used during recovery for resynthesizing glycogen and as oxidative fuel during aerobic exercise [11]. However, because of selective vasoconstriction during apneic sports, lactate removal from working muscles and its transport could be impaired, resulting in a limited oxidation which may lead to its accumulation [2]. Lactic acid accumulation and hypercapnia during apnea may lead to severe acidosis, which can limit performance [8].

There are six FD disciplines, in which regular competitions are held by AIDA, the International Association for the Development of Apnea, the main global organizing body. These competitions involve three pool- and three open-water disciplines, presenting varying physiological demands during continued apnea (Table 1) [2,3,12]. In static apnea (STA) the diver produces the maximal time resting face-down at the surface, and no work or depth influences the performance [3]. The two dynamic apnea disciplines, with fins (DYN) and without fins (DNF), share the aim to cover the maximal horizontal distance swimming in a pool [2]. In the deep diving disciplines "constant weight" (CWT) and "constant weight no fins" (CNF) the diver swims down and then up along a vertical line, and in "free immersion" (FIM) the diver pulls him/herself down and up along a vertical line using the arms [12]. In addition there are two categories of deep diving without competitions but in which individual records are recognized: "variable weight" and "no limit." which are performed by a limited number of individuals, and therefore not included in this study.

In SSW, swimmers perform a well-timed and aesthetical program of synchronized routines in the water in solo, duet or team events, with the aim of being judged and obtaining the highest marks of the competition. The program includes a range of technically and physically demanding routines involving intense whole-body work, performed during apneic episodes interspaced with short breathing intervals [13]. 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. The free routine allows more flexibility, as there are no figure requirements. Routines last between two and five minutes, with the swimmer spending up to two-thirds of the routine time underwater [13,14].

Sufficient apneic duration is a prerequisite for performance in these underwater sports disciplines, expressed in its most fundamental form in STA. Work intensity, muscle mass recruited and depth may affect performances in other disciplines [12]. Several factors will likely influence the net lactate accumulation (NLA), i.e., the difference in blood lactate concentration between pre- and post-apnea. These factors likely include apneic duration, the nature and intensity of exercise, and possibly different aspects of the athletes' fitness [2,13,15]. There are few previous studies on blood lactate accumulation during FD or SSW disciplines in competition [1,2,13,16]. The aim was therefore to determine NLA in these disciplines during real competition, and to provide information about the use of the anaerobic system based on NLA. We hypothesized that STA would show the lowest NLA due to the resting conditions and that, despite intense exertion, the SSW disciplines would display lower NLA compared to the other FD disciplines due to the intermittent breathing.

METHODS

Subjects

A total of 43 elite freedivers (17 females) and 34 elite female synchronized swimmers, all having competed at national and/or international level for at least two years, volunteered for the study. Their mean (SD) ages were 31 (7) for FD and 18 (3) for SSW. Height and weight were 174 (8) cm and 71 (11) kg for freedivers and 165 (7) cm and 54 (6) kg for SSW.

The study was approved by the local research ethics committees and conducted in accordance with the Declaration of Helsinki [17]. Volunteers had undergone a medical examination and received oral and written information before giving informed consent, with parental permission when under 18 years of age. Most subjects participated in more than one event within each of the two sports (FD or SSW); numbers per discipline are indicated in Table 1.

Study design

Procedures

The study was conducted during three international freediving competitions during 2010 and 2011, and at the 2011 Spanish National synchronized swimming championships. All dives and routines were studied during competition performances. Subjects who participated in more than one discipline had a minimum of one day of rest between FD and more than two hours of rest between SSW disciplines. Depth disciplines were performed in the sea, and all other disciplines in a pool, both at a water temperature of 26°C [1].

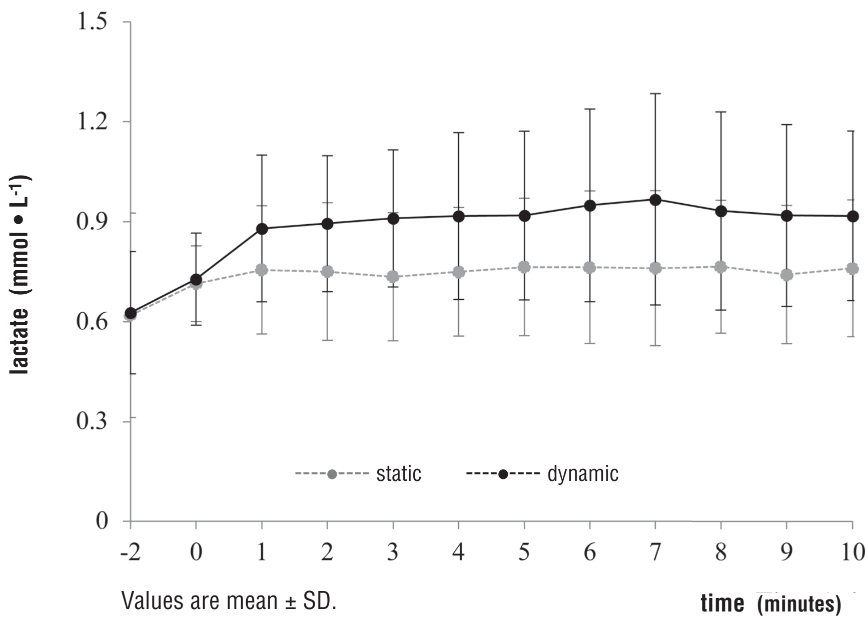
Determining sampling time

As an indicator of anaerobic performance after eupneic exercise, capillary lactate concentrations are usually assessed at one, three, five, seven and 10 minutes post-exercise [18]. However, in SSW sampling at three, five, seven and 10 has been shown to be an adequate time span for detecting post-exercise peak lactate accumulation in this kind of athlete [13]. There are no studies showing which could be the best time span applicable to apneic sports. For practical purposes, in a competition situation it would be necessary to limit the sampling period. Therefore, in a separate test prior to competition data collection, the pattern of post-exercise lactate concentration (La_{post}) after apneic events was determined in 10 young recreational freedivers. They performed maximal resting apneas as a model for STA, and, as a model for dynamic disciplines, they conducted apneas during 100 W at 60 RPM work on a cycle ergometer. Lactate samples were taken from a venous catheter before and every minute after the apneas for 10 minutes. The two tests were performed in a weighted order at different days. Post-apnea lactate reached a steady level after two to three minutes in both STA and dynamic tests, with no further changes observed across the next eight minutes (Figure 1).

In all FD disciplines, divers must perform a "surface protocol" after the dives to ensure they are not too hypoxic, or they are disqualified. After 30 seconds, the judgment is given, and the athlete is then moved to the side of the platform where we can measure lactate. Based on this setup, post-apneic samples were taken at three minutes after performance in all disciplines. These values were compared with reference values taken one to two minutes before the events, after warm-up.

For practical purposes, different sampling sites were used between FD and SSW disciplines. Most freedivers use a wetsuit with a hood; hands are exposed and usually not cold, so finger capillary samples were used. However, SSW athletes are minimally dressed, and their fingers are often cold. Because of this, blood was drawn from the ear. After competitive performance and before the blood draw, regular water was used to clean the puncture area of saline and chlorine, with sterile gauze used to dry the area. Then, 10 μL of capillary blood was drawn and analyzed in duplicate.

FIGURE 1. Laboratory pre-test
Post-apnea lactate determination during simulated static and dynamic apnea



Values are mean ± SD.

In a study addressing the site for capillary blood collection, no differences were found in simultaneous capillary samples drawn from ear and fingertip [19]. It could be speculated that differences in divers' cold exposure during sampling (e.g., before dives, dry and warm but after dives wet and cold) may influence the lactate response [20]. However, with the individuals having similar sampling conditions, NLA values should be comparable between disciplines.

All reference pre-exercise lactate concentration (La_{pre}) samples were taken while subjects were resting out of the water. Post-apnea tests in SSW and FD pool disciplines were taken with subjects resting on land, while in depth disciplines, freedivers remained resting in the water until sampling.

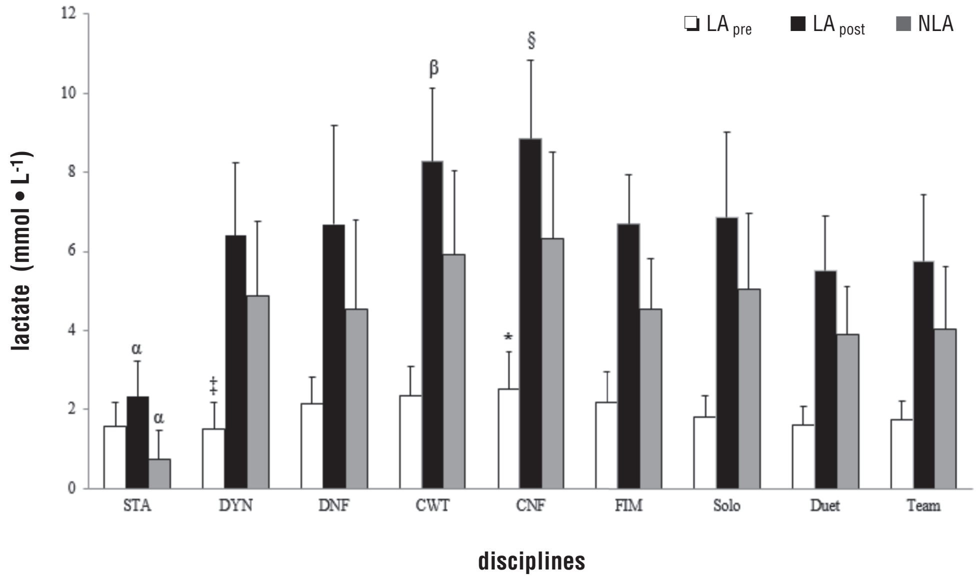
Samples were analyzed using a lactate photometer (Diaglobal DP100, Berlin, Germany) or Lactate Scout Test Strips (SensLab GmbH, Germany) with a mean difference of 1.05%–3.67% [21]. Most subjects who competed in STA fasted in the morning before competition [22], while subjects in other disciplines ate a light breakfast two to three hours before the start. In all cases, athletes were allowed to drink water ad libitum during competitive sessions.

Performances and durations were determined in FD disciplines using a stopwatch and registered from competition results. To determine apneic duration in SSW solo and duet, each routine was videorecorded (Panasonic AG-DVX100BE 3-CCD Mini-DV Cinema Camcorder). Recorded images were decoded (LINCE, version 1.1, Barcelona, Spain) [23]. Time for episodes with complete facial immersion – with chin and forehead included – was determined [24], and its percentage of the entire routine duration calculated. For the SSW team, no apneic duration was recorded, due to difficulty filming the individual competitors.

Statistical analysis

Data are presented as mean and standard deviation (±SD) for separate disciplines or similar disciplines pooled (all FD disciplines except STA, due to its lack of work, and all SSW disciplines, respectively). Because of the unbalanced design and the existence of within-subject correlated data (most athletes participated in more than one event) a linear mixed-effects model [25] was used to compare La, NLA and apnea duration among disciplines. Pairwise comparisons with Bonferroni correction were used to identify significant

FIGURE 2. Mean ± SD blood lactate concentration and net lactate accumulation for each discipline



Significant differences at P<0.05 are indicated: α for STA vs. all other disciplines; ‡DYN vs. DNF; β for CWT vs. SSW team; * for CNF vs. STA, team SSW, and DYN; and § for CNF vs. FD pool disciplines and all SSW events.

differences between estimated means. Estimated means for each period of time with the 95% confidence interval are presented. The relationship between apnea duration and NLA was evaluated using Pearson's correlation analysis. P < 0.05 was considered significant.

RESULTS

Pre-apnea blood lactate

For STA, which was treated separately due to its resting conditions, mean (SD) La_{pre} was 1.6 (0.2) mmol•L^{-1}. For the rest of the FD disciplines, La_{pre} was higher in general (2.0 (0.8) mmol•L^{-1}) than in pooled disciplines of SSW (1.71 (0.5) mmol•L^{-1}, P = 0.006).

La_{pre} was highest among all separate disciplines in CNF 2.5 (0.9) mmol•L^{-1} (Figure 2). This value was higher compared to STA 1.6 (0.6) mmol•L^{-1} (P = 0.034), DYN 1.5 (0.7) mmol•L^{-1} (P = 0.004), and SSW team 1.7 (0.5) mmol•L^{-1} (P = 0.038). In addition, DNF had a higher La_{pre} at 2.1 (0.7) mmol•L-1 than DYN at 1.5 (0.7) mmol•L^{-1} (P = 0.023; Figure 2).

Post-apnea blood lactate

For STA, La_{post} was 2.3 (0.9) mmol•L^{-1}. For all FD disciplines except STA pooled, La_{post} was 7.1 (2.1) mmol•L^{-1}, whereas in all SSW events pooled it was 5.9 (1.8) mmol•L^{-1} (P = 0.001; Figure 2).

The highest La_{post} value among all separate disciplines was found after CNF 8.8 (1.9) mmol•L^{-1}, followed by the rest of the FD depth disciplines: CWT 8.26 (1.9) mmol•L^{-1} and FIM 6.7 (1.2) mmol•L^{-1}. La_{post} was significantly higher in CNF than in SSW events; solo: 6.9 (2.2) mmol•L^{-1} (P = 0.014), duet: 5.5 (1.4) mmol•L^{-1} (P < 0.001); and team: 5.8 (1.68) mmol•L^{-1} (P < 0.001), and FD pool disciplines; STA: 2.3 (0.9) mmol•L^{-1} (P < 0.001), DYN: 6.4 (1.8) mmol•L^{-1} (P = 0.009) and DNF: 6.7 (2.5) mmol•L^{-1} (P = 0.035). The La_{post} after STA was lower than in all other disciplines (P < 0.001; Figure 2).

Net lactate accumulation in pooled FD disciplines except STA (5.1 (2.0) mmol•L^{-1}) was a higher than in all SSW disciplines pooled (4.2 (1.6) mmol•L^{-1}, P = 0.032). When individual disciplines were compared,

TABLE 2. Apneic duration (A), distance traveled (D) and velocity (υ) for studied disciplines

	DISCIPLINES							
	STA	DYN	DNF	CWT	CNF	FIM	solo	duet
A (s)	293 ± 11*	111 ± 12	138 ± 14	118 ± 12	132 ± 14	150 ± 14	95 ± 16	102 ± 20
D (m)	–	227 ± 83*	206 ± 82*	120 ± 43	100 ± 24	118 ± 26	–	–
υ (m•s^{-1})	–	2 ± 1*	1 ± 0.4†	1 ± 0.1	0.8 ± 0	0.8 ± 0.1	–	–

See abbreviations in Table 1. Differences (P<0.05) are indicated: *for A vs. all other disciplines; *for D vs. CWT, CNF, and FIM; *for υ vs. DYN, DNF and all other depth disciplines; and † for υ vs. CNF and FIM. Data are mean ± SD.

the highest NLA was found in CNF 6.3 (2.2) mmol •L^{-1}, followed by CWT 5.9 (2.1) and SSW solo 5 (1.9) mmol•L^{-1}. STA showed the lowest NLA 0.7 (0.7) mmol•L^{-1} compared to all other disciplines ($P < 0.001$; Figure 2).

Performance

STA, as expected by its nature, showed the longest apneic duration when compared with all the other disciplines, with an average duration of four minutes, 53 (11) seconds ($P < 0.05$; Table 2). FIM involved the second-longest duration at two minutes, 30 (14) seconds. In the SSW solo event, total duration of performance was two minutes, 34 (28) seconds and apnea represented 64 (5)% of the routine time. In the duets, the total performance duration was two minutes, 57 (31) seconds, with an apnea percentage of 59 (6) %.

With STA values excluded, NLA was positively correlated to apnea duration for all other disciplines ($r = 0.351$; $P < 0.01$).

DISCUSSION

All studied FD and SSW disciplines were associated with NLA, showing that there is great contribution of anaerobic metabolism in these athletes. This confirms earlier reports of NLA in some of these disciplines studied separately [2,13]. This shows that these disciplines, which involve voluntary apnea, may last beyond the "aerobic dive limit" (ADL) during competition [26]. While not typical – for example, harvest divers [27] who have to limit surface time and thus cannot metabolize lactic acid, have to remain within ADL – this is similar to observations of dives extended beyond the ADL in certain marine mammals such as deep diving seals [3,26].

As the intention in these competition sports is to make one single maximal performance, the resulting long recovery period needed for oxidation of the accumulated lactate or gluconeogenesis is unproblematic. Moreover, our findings are with levels found in previous studies in eupneic sports such as swimming [28], floor exercises in artistic gymnastics [29], competitive aerobic [30] or figure skating on ice [31].

STA showed lower NLA than all other disciplines, and the other FD disciplines pooled showed higher NLA than SSW disciplines pooled, in accord with our hypothesis, showing an influence of both exercise level and apneic duration on NLA. The highest La_{post} was seen after CNF, where large muscle groups of both the upper and lower body are at work [12]. Whole-body work is also seen in SSW disciplines, but apneic duration is shorter in such events, as breathing episodes of varying duration – though mostly short – interrupt the apneas [14]. FIM, however, despite the slightly longer apneic duration compared with CNF, had lower La_{post}, which was likely due to the involvement of a small working muscle mass of the upper body only when the diver pulls down and up along the line using the arms. Also, arm muscles have been shown to extract less oxygen than leg muscles [32], leaving more room for further extraction later, which could probably reduce the anaerobic component over time if exertion is kept within limits [32].

One could perhaps expect that DNF, with similar involvement of both upper and lower body muscles but longer apneas than CNF, should result in a higher NLA. The distance traveled is also longer for DNF in the pool, where the diver must swim all the way and while the vertical diving for depth in CNF involves a phase of passive "freefall" below the point of neutral buoyancy, which would likely reduce metabolism [12].

Then why is CNF showing the highest NLA? We speculate that the CNF freefall phase may allow the diving response to develop to its full extent, limiting blood flow to previously supplied working muscle [12]; when the diver turns and has to swim up against negative buoyancy, swimming muscles must likely rely entirely on myoglobin stores and anaerobic energy.

Yet another contribution to the high La_{post} values among apnea disciplines for depth could be that the deep diver cannot interrupt the apnea until returning to the surface once depth is reached, while in a pool discipline the diver can surface at any time.

STA showed the lowest NLA compared to all other disciplines, most likely due to the minimal skeletal muscle work involved despite its much longer apneic duration compared to all other disciplines. The NLA in STA would show that a degree of anaerobic metabolism sufficient to cause accumulation does occur even without active muscle work, which accords with earlier observations [3]. After single record STA performances, values as high as 5 $mmol{\cdot}L^{-1}$ have been reported [2]. STA has previously been shown to result in a greater fall in heart rate and peripheral vasoconstriction than in the dynamic disciplines. This will contribute to the conservation of O_2, but could result in enhanced lactate production [2,33,34]. On the other hand, fasting, often done by athletes before STA, may have decreased lactic acid accumulation, as its formation, exchange and utilization represents important means of distributing carbohydrate energy sources after a carbohydrate meal [35]. In experienced divers fasting is associated with prolongation of apnea via metabolism-limiting mechanisms [22]. However, with inexperienced subjects, fasting may decrease apneic duration, suggesting that divers may get closer to hypoxic loss of consciousness [36]. Thus, taken together, this study would suggest that the recruitment of muscle mass is a more important factor than apneic duration per se for NLA, but among disciplines involving similar muscle work, apneic duration is clearly important.

In SSW disciplines, the mostly short breathing pauses would lower the NLA, likely by increasing oxygen stores and aerobic metabolism and by allowing some lactate metabolism during the events, thus resulting in lower NLA than in FD disciplines.

Compared to earlier observations on post-event lactate values in FD [12], the La_{post} values in the present study were similar for depth disciplines, but lower than those reported by Schagatay (2010) for dynamic disciplines [2]. This could be due to the level of the athletes included. In the present study, we included a sample of all the competitive athletes, while in DYN and DNF in the Schagatay (2010) study, only the best athletes were included [2]. It seems likely that lactate tolerance may be a factor determining performance in apnea sports. However, lactate production may not be enhanced in top divers: when comparing blood lactate levels in divers and non-divers after resting and working apneas, Joulia, et al. (2002) found lower lactate levels in the divers, suggesting the presence of some adaptive mechanisms to reduce lactate metabolism [37].

All studied disciplines were associated with pre-event lactate levels above the normal resting range, with the highest levels seen in the depth disciplines performed in open-water, with values of La_{pre} similar to findings in some disciplines studied in competition before, but higher than those reported before from an open-sea training in FIM, and before training dives in a pressure chamber [6,12,38]. Competition is a challenging situation, evoking higher psychophysiological responses in the participant than training events [39]. Enhanced stress in competition has been shown to lead to less diving bradycardia in STA events [40]. As a result of higher sympathetic activation, stimulation of muscle glycogenolysis and hepatic neoglucogenesis may occur, and this in turn could induce a higher production of muscle lactate before competitive performances than in training [41].

Could other factors have elevated La_{pre} from resting levels? Before the freediving disciplines performed at sea, divers had to travel to the competition platform, which, despite assistance from their coaches, involved some physical work. Warm-up in all disciplines except STA may also have elevated La_{pre}, despite being conducted ~15 minutes before the performances. Among FD pool disciplines, the higher La_{pre} found in DNF compared to DYN may reflect more demanding work during the warm-up, as both upper- and lower body stretching is involved.

Further studies should be directed to more specific study of the separate relative influence of levels and types of work and apneic duration on NLA, and to determine how much lactate could be oxidized during performance in disciplines with intermittent breathing.

LIMITATIONS

Due to restrictions imposed by the official rules and for ecological validity reasons, we were constrained to monitor the post-exercise blood lactate concentration within a limited period. There were, therefore, some differences in sampling procedures between the studied groups (FD vs. SSW), and between tests (venous blood vs. capillary blood). Moreover, the differences in cold exposure (sea vs. pool), the potential differential washout time of lactate in the different dives, the general competitive stress [42], and diet [43] could possibly have affected the results. However, these were controlled so as not to cause general differences, and especially when a majority of the subjects within each sport participated in most disciplines.

The limited group sizes, as well as age and sex differences could possibly affect these responses, although all subjects were fairly young athletes, and sex has not been shown to cause any major differences in responses relating to diving performance [44].

CONCLUSION

The present study shows that NLA occurs in all studied disciplines of FD and SSW. The highest La_{post} levels are reached in disciplines involving both exercise by large muscle groups and long breath-holding periods; it is lowest in STA, due to the resting conditions, in line with our hypothesis. The SSW disciplines showed intermediate levels despite high levels of exertion, due to the intermittent breathing. We concluded that NLA is influenced by both the type of work and the apneic duration, with reduced NLA in SSW due to the intermittent breathing, suggesting that some of the lactate produced could be oxidized during performance. ■

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