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Breath-hold diving strategies to avoid loss of consciousness: speed is the key factor

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ABSTRACT

The aim of this study was to investigate the impact of breath-hold diving strategies regarding loss of consciousness (LOC). Three international competitions were examined through video in constant weight diving with (CWT) or without (CNF) fins. We analysed three breath-hold parameters (time, speed, and movements count) for the following phases: active descent, passive descent, turning, and ascent. Divers who had LOC during CNF were slower in the active descent phase, faster in the passive descent phase with a longer turn, and slower in the ascent phase than divers who did not have LOC. They also had lower amplitude and higher frequency. Men were deeper (72.9 m vs. 56.3 m) for a longer dive time (181.1 s vs. 154.6 s), faster, with a greater amplitude than women. In CWT, divers with an LOC had longer dive times (197 s vs. 167 s) with a faster active descent phase. Men had lower amplitude and greater frequency than women. This is the first study showing that breath-hold divers undergoing an LOC event shown differences in efficiency during CWT and CNF regarding velocities, amplitudes, and frequencies. In conclusion, our results suggest that the speed parameter during active descent phase influence the LOC.

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Apnoea; performance improvement; hypoxic blackout; management of loss of consciousness; diving strategy

Introduction

Increasingly popular and originating from practices related to the livelihood of populations, breath-hold (BH) diving is now practised all over the world. The philosophy changed in the second half of the 20th century and has seen a recent development of in-depth competitions with or without fins: Constant Weight (CWT), Constant Weight No Fin (CNF), and Free Immersion (FIM). During CWT and CNF, BH divers (BHDs) descends and ascends with or without the use of bifins/monofin and without pulling on the rope. The rules and objectives in the competition are similar for these two disciplines: to go as deep as possible while going back up by executing an exit protocol showing the perfect mastery of the performance. The loss of consciousness (LOC) is a criterion disqualifying the performance. The discipline, which then became performance-oriented, began to attract the BHDs from the swimming world, which changed practices, leading to the desire to reach

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increasingly impressive depths. In competition, the BHDs must reach a performance announced *a priori*, grab a tag, go back to surface, and correctly perform the surface protocol. According to AIDA (Association Internationale pour le Développement de l'Apnée), the current CWT and CNF records are 130 m for men and 107 m for women, and 102 m for men and 73 m for women, respectively. To achieve such a performance, the human body benefits from a set of physiological adaptations gathered under the concept of 'diving reflex' that is triggered during BH. This reflex is characterised by peripheral vasoconstriction, bradycardia, and splenic contractions (Costalat et al., 2015; Fitz-Clarke, 2018). The diving reflex takes place to help reduce the oxygen consumption, delay adverse effects of hypoxia and hypercapnia (Fitz-Clarke, 2018). BH induced hypoxaemia can cause dramatic effects ranging from loss of motor control to loss of consciousness (LOC) of BHDs (Costalat et al., 2017). Loss of motor control include signs such as confusion, affected postural control, spasms or speech problems and LOC disorders manifest themselves as stroke-like symptoms in a gradual cognitive decline with most of the time eyes rolling back, face dipping and myoclonic jerks, which may be followed by an abrupt collapse (Fitz-Clarke, 2018; Schipke et al., 2019). According to Lindholm (2007), 9.7–11.1% of BHDs were disqualified due to loss of motor control or LOC over six competitions from 1998 to 2004 (Lindholm, 2007). Based on publicly available data reported in the Divers Alert Network (DAN) annual report, 78% of the diving-like activity incidents were qualified as lethal from 2004 to 2016 (Buzzacott & Denoble, 2018). These statistics were directly linked to unsupervised recreational practices, and therefore to the absence of appropriate safety measures during competitions in the past. Thanks to the presence of both medical staff and safety divers now, this number is reduced to 8.3% (Buzzacott & Denoble, 2018).

The focus of most research has so far been the physiological aspects of performance in BHDs to prevent LOC. These studies have shown that LOC and long BH could affect the integrity of the nervous system in the long term (Billaut et al., 2018; Gren et al., 2016; Linér & Andersson, 2009). To prevent LOC, clarified details of the different dive parameters implied during the CWT and CNF dives appear as a fully complementary and relevant approach. Recent advancements in digital filming technologies can help to achieve such a goal through video analysis widely developed in analogous sports such as swimming (Takeda et al., 2020). In this context, it seems valuable to examine the impact of BHD strategies on adverse events such as LOC.

This study aimed to determine the relationships between LOC and diving strategies in CWT and CNF by video analysis of three BH parameters (time, speed, and movements count) for the following phases: active descent, passive descent, turning, and ascent. We hypothesised that, (i) a high speed and frequency, and a low amplitude increase the risk of LOC, and (ii) these speed, frequency, and amplitude parameters are managed differently in CWT and CNF.

Methods

Selection and description of participants

The three BH parameters (time, speed, and movements count) of BHDs were retrospectively analysed through videos collected from three international freediving competitions that took place in 2018. Analyses were conducted on 21 BHDs in CNF (14 men and 7 women), and 37 BHDs in CWT (20 men and 17 women). All BHDs performed their usual ventilatory protocol and lung packing to increase the total air volume in their lungs before the dive. Safety divers were present at 25 m to prevent incidents related to LOC according to freediving competition rules. At the end of the dive, judges analysed their surface protocol to notice any form of hypoxia following the AIDA or the 'Confédération Mondiale des Activités Subaquatiques' (CMAS) rules.

Technical information

Longomatch 1.3.7 (Fluendo) has been used to encode CNF, and CWT performance. Data processing and analysis were carried out in Python 3.7 and Microsoft R Open 3.5. To determine the variations of the strategies used, the dive was divided into several phases with (i) the active descent phase, (ii) the passive descent phase, (iii) the turn phase and (iv) the ascent phase (Figure 1). To automate the phase determination, motion markers were transformed into a vector representing their cumulative sum

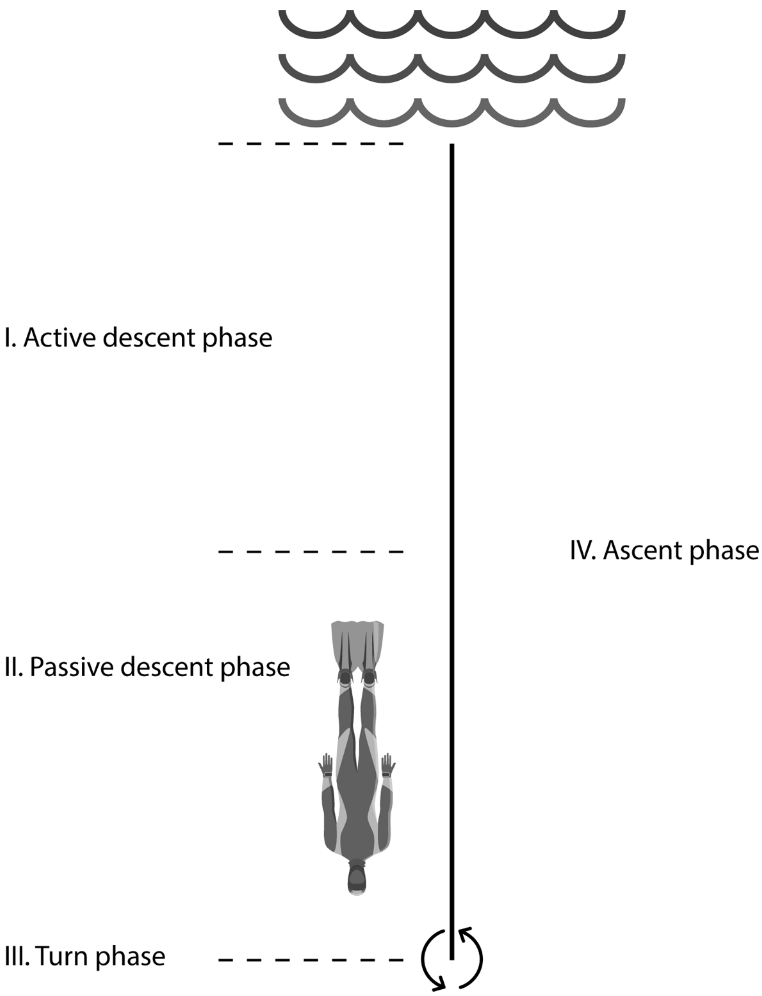

Figure 1. Schematic representation of the distribution of the different phases in breath hold diving.

with their time and associated depth. The velocity has been then calculated on the depth vectors and time. The end of the active descent (i) could be detected because of the considerable amount of time between the last movement and the initiation of the turn. The passive descent (ii) takes place from the moment the movement stops until the diver grabs the cable. The turn (iii) and therefore the ascent (iv) are directly determined by the video analysis. Once the phases have been determined, key values were extracted from them, i.e.: the distance (m), the duration (s), the speed (m/s), the movement count (noted n), the frequency (n/s), and the amplitude defined as the division of the speed by the frequency. Besides, the ratio of time and distance spent in the active (i) and passive (ii) phases are determined with the total fall (i and ii). For the CNF, the propulsive movements of the arms and legs were counted with their associated time and depth. For CWT, key points have been defined to quantify movements of hip, knees and ankles. Each passage of the joint into the closed position then counts as a realised movement. Each movement was then characterised by the time of its realisation and depth. Changes in arm position were noted in an analogous manner. No woman had suffered an LOC for CNF in any of the competition; hence, no analysis between genders has been computed in this discipline.

Statistics

Once the key values for each BHD in the different disciplines have been determined, the normality of the variables were tested by the Shapiro–Wilk test and the homoscedasticity by a Levene or Bartlett test (Schultz, 1985). First, analysis was within-discipline comparisons: normal and homoscedastic variables (i.e., dive time, maximal depth, velocity, amplitude, and frequency) were compared between genders and the presence or absence of LOC by a two-way ANOVA. Otherwise, an ANOVA is performed according to the Aligned Rank Transform (ART) method (Wobbrock et al., 2011) to permit the calculation of interactions where more traditional nonparametric tests (i.e., Mann–Whitney U) prevent it. Genders were compared on LOC occurrence through Fisher's exact test. Second, analysis was between-discipline comparison: after a Principal Component Analysis (PCA), we confronted with a two-way ANOVA CNF and CWT on comparable variables (i.e., speed of phases, dive time, achieved depth, and ratios between active, and passive phases). Disciplines were compared on LOC occurrence through a Fisher's exact test. Distances, timestamps and velocities can be directly compared between CNF and CWT. The results were expressed as the mean value ± SD. A p-value <0.05 was considered statistically significant for all analyses. P-values are corrected using Benjamini–Hochberg FDR (Hochberg, 1988). For all features, the effect size is computed as Hedges's g (Hedges, 1981) with a bias correction defined as $\frac{n-3}{n-2.25}\sqrt{\frac{n-2}{n}}$ where $n = n_1 + n_2$ (Durlak, 2009).

Results

Within-discipline comparison: CNF and CWT

Constant weight no fin (CNF)

The results of ANOVA between genders and LOC showed significant main effects on dive parameters, but no significant interaction (Table 1). Most dives were between 41 and 94 metres (Figure 2a,b).

Table 1. Two-way ANOVA between Gender and LOC Constant Weight No Fin (CNF). (i) Active descent phase; (ii) Passive descent phase; (iii) turn; (iv) Ascent phase. Values are presented as mean ± SD. g is defined as Hedges' g corrected for small sample sizes.

	CNF							
	Women	Men	g	p-value (<F)	Valid	LOC	g	p-value (<F)
Total Time	154.65 ± 25.26	181.08 ± 28.31	0.88	<0.001	171.87 ± 30.95	174.63 ± 24.49	0.08	<0.001
Max. Depth	56.29 ± 11.88	72.79 ± 14.24	1.11	<0.001	67.94 ± 15.81	63.33 ± 14.98	−0.27	0.001
Speed (i)	0.75 ± 0.08	0.87 ± 0.14	0.92	<0.001	0.85 ± 0.13	0.71 ± 0.04	−1.08	<0.001
Amplitude (i)	2.40 ± 0.59	3.96 ± 0.96	1.66	<0.001	3.51 ± 1.20	2.99 ± 0.42	−0.41	0.014
Frequency (i)	0.32 ± 0.05	0.23 ± 0.03	−2.29	0.020	0.26 ± 0.06	0.24 ± 0.02	−0.37	<0.001
Time Ratio (i)	0.59 ± 0.19	0.38 ± 0.07	−1.67	<0.001	0.44 ± 0.17	0.43 ± 0.14	−0.09	1.000
Distance Ratio (i)	0.60 ± 0.18	0.38 ± 0.07	−1.74	0.002	0.46 ± 0.16	0.41 ± 0.12	−0.32	0.698
Speed (ii)	0.80 ± 0.13	0.90 ± 0.08	0.81	<0.001	0.86 ± 0.11	0.89 ± 0.11	0.22	0.003
Time Ratio (ii)	0.36 ± 0.18	0.58 ± 0.08	1.71	<0.001	0.51 ± 0.17	0.50 ± 0.14	−0.03	1.000
Distance Ratio (ii)	0.40 ± 0.18	0.62 ± 0.07	1.74	0.002	0.54 ± 0.16	0.59 ± 0.12	0.32	0.698
Time (iii)	4.22 ± 1.56	4.28 ± 1.66	0.03	0.006	4.17 ± 1.67	4.77 ± 1.03	0.34	0.027
Speed (iv)	0.73 ± 0.07	0.79 ± 0.08	0.66	<0.001	0.78 ± 0.07	0.72 ± 0.13	−0.60	0.002
Amplitude (iv)	2.29 ± 0.24	2.59 ± 0.38	0.81	<0.001	2.55 ± 0.37	2.17 ± 0.15	−0.97	0.003
Frequency (iv)	0.32 ± 0.02	0.31 ± 0.05	−0.25	<0.001	0.31 ± 0.04	0.33 ± 0.04	0.47	0.004

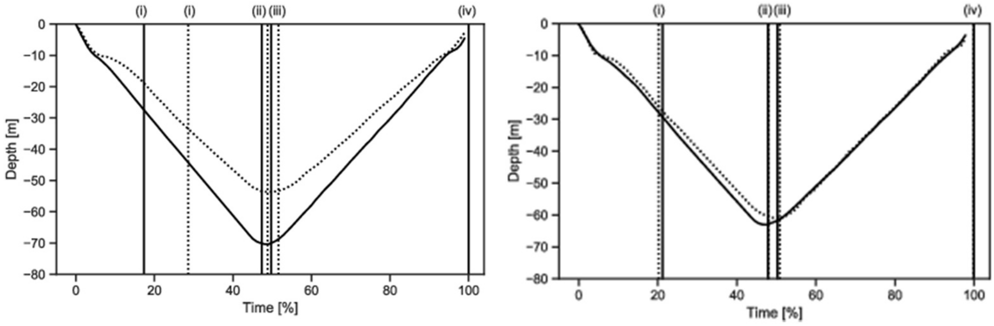

Figure 2. Typical normalised performance in CNF.
Typical normalised performances of men (solid lines) versus women (dashed lines). Each vertical solid and dashed line is indicating the end of a phase for men and women, respectively (2a). For divers, typical normalised valid performances (solid lines) versus performance resulting in LOC (dashed line). Each vertical solid and dashed line is indicating the end of a phase for valid and LOC, respectively (2b). (i) Active descent phase; (ii) passive descent phase; (iii) turn; (iv) Ascent phase.

Constant weight (CWT)

The results of ANOVA between genders and LOC showed significant main effect on dive parameters without significant interaction (Table 2). According to Fisher's exact test, women do not have more LOC than men (p-value = 0.667). Most dives were between 60 and 105 metres (Figure 3a,b).

Table 2. Two-way ANOVA between Gender and LOC in Constant Weight (CWT). (i) Active descent phase; (ii) passive descent phase; (iii) turn; (iv) Ascent phase. Values are presented as mean ± SD. d is defined as Hedges' g corrected for small sample size.

	CWT							
	Women	Men	g	p-value (<F)	Valid	LOC	g	p-value (<F)
Time	157.56 ± 36.37	183.84 ± 23.78	0.83	0.020	166.83 ± 30.26	197.30 ± 34.95	0.94	0.040
Max. Depth	76.24 ± 17.69	103.15 ± 12.58	1.69	<0.001	88.32 ± 20.37	103.50 ± 14.61	0.73	0.100
Speed (i)	1.05 ± 0.11	1.12 ± 0.14	0.55	0.120	1.06 ± 0.12	1.24 ± 0.07	1.51	0.002
Amplitude (i)	1.88 ± 0.44	2.03 ± 0.55	0.28	0.440	1.92 ± 0.51	2.16 ± 0.42	0.47	0.320
Frequency (i)	0.59 ± 0.15	0.59 ± 0.17	0.01	0.970	0.59 ± 0.17	0.59 ± 0.11	−0.02	0.950
Time Ratio (i)	0.51 ± 0.17	0.36 ± 0.16	−0.83	0.010	0.46 ± 0.18	0.28 ± 0.07	−0.95	0.006
Distance Ratio (i)	0.55 ± 0.17	0.38 ± 0.16	−1.02	0.006	0.48 ± 0.19	0.33 ± 0.07	−0.82	0.010
Speed (ii)	0.85 ± 0.14	1.01 ± 0.08	1.36	<0.001	0.93 ± 0.14	0.99 ± 0.13	0.39	0.500
Time Ratio (ii)	0.50 ± 0.17	0.64 ± 0.16	0.82	0.010	0.55 ± 0.18	0.72 ± 0.07	0.97	0.005
Distance Ratio (ii)	0.45 ± 0.17	0.62 ± 0.16	1.02	0.006	0.52 ± 0.19	0.67 ± 0.07	0.82	0.010
Time (iii)	3.17 ± 1.41	2.55 ± 0.87	−0.52	0.220	2.73 ± 1.23	3.37 ± 0.62	0.53	0.100
Speed (iv)	1.03 ± 0.13	1.25 ± 0.16	1.48	<0.001	1.16 ± 0.18	1.09 ± 0.18	−0.37	0.110
Amplitude (iv)	1.56 ± 0.32	1.36 ± 0.26	−0.68	0.040	1.46 ± 0.32	1.39 ± 0.23	−0.21	0.780
Frequency (iv)	0.69 ± 0.19	0.96 ± 0.22	1.34	<0.001	0.84 ± 0.25	0.79 ± 0.14	−0.19	0.310

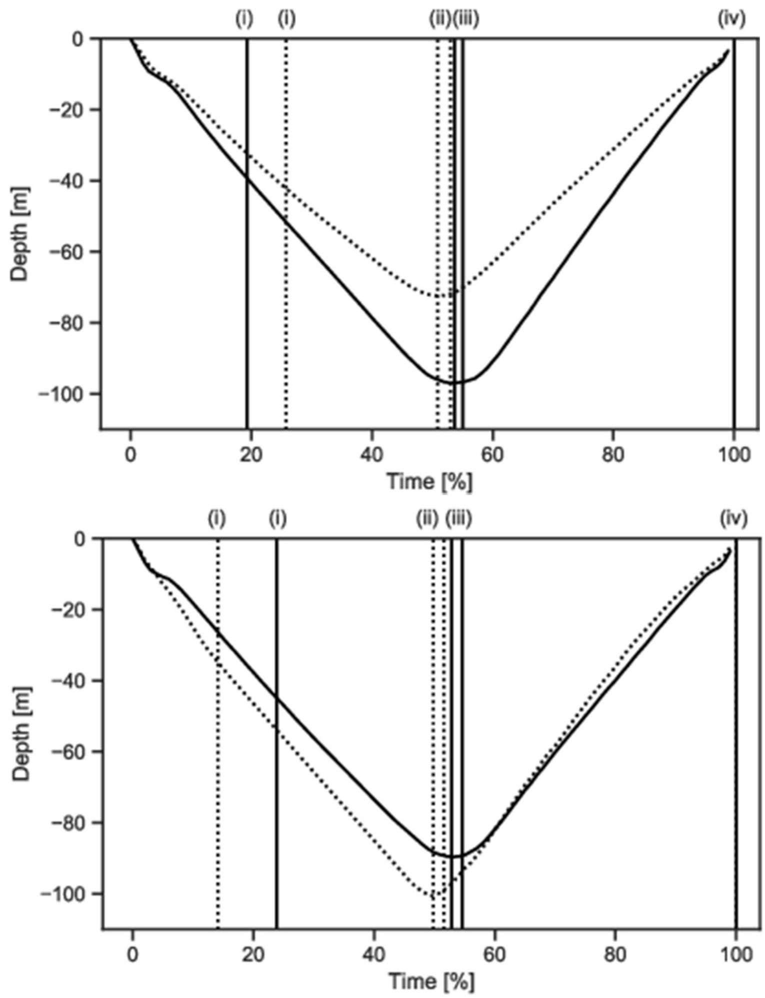

Figure 3. Typical normalised performance in CWT. Typical normalised performance of men (solid lines) versus women (dashed lines). Each vertical solid and dashed line is indicating the end of a phase for men and women, respectively (3a). Typical normalised valid performances (solid lines) versus performance resulting in LOC (dashed lines). Each vertical solid and dashed line is indicating the end of a phase for valid and LOC, respectively (3b). (i) Active descent phase; (ii) passive descent phase; (iii) turn; (iv) Ascent phase.

Between-discipline comparison: CNF vs. CWT

In CNF, the mean performance was 67.29 ± 15.41 m vs 90.78 ± 20.19 m in CWT. Dives' maximal depths ranged from 82 metres (CNF) to 130 metres (CWT) for a total duration of apnoeas from 114 seconds to 254 seconds. Speeds ranged from 0.63 m/s (CNF) to 1.26 m/s (CWT) (Figure 4). The Fisher's exact test of LOC occurrence between CNF and CWT is not significant (p-value = 0.998).

ANOVA showed significant differences between CNF and CWT on the achieved depth, but not for the dive time. Otherwise, CWT was faster in all phases ($p < 0.001$). Analysis on the speed variable during ascent phase showed a significant interaction ($p < 0.001$). A posthoc t-test with Benjamini–Hochberg FDR correction showed significant differences between LOC and CNF ($p < 0.01$), and between LOC and CWT ($p = 0.001$) (Table 3).

In CWT, LOC dives were at 1.24 ± 0.07 m/s vs 1.06 ± 0.12 m/s for valid performance. In CNF, these values were set at 0.70 ± 0.04 m/s and 0.86 ± 0.13 m/s. The visualisation offered by the first two components of the PCA, explaining 60% of the total variance, is showing the differences between the disciplines (Figure 5). The maximal depth (contribution of 0.105), the speed of the active descent phase (0.092), the frequency (contribution of 0.120), and the speed of the ascent phase (0.090) are the most important features in the definition of the first component. The second component is mostly defined by the amplitude of the active descent phase (contribution of 0.123), distance and time ratios of the active descent phase (respective contributions of 0.139 and 0.129), and distance and time ratios of the passive descent phase (contributions of 0.139 and 0.098).

Table 3. Post-hoc t-test for the variable vp1 (speed in the active phase) between type (CNF, CWT) and LOC. 'p-corr' is the p-value corrected through Benjamini–Hochberg FDR correction. Original p-value reported as 'p-unc'.

Contrast	type	T	p-unc	p-corr
type	-	−6.913	<0.001	
LOC	-	−0.757	0.469	
type * LOC	CNF	3.783	0.004	0.004
type * LOC	CWT	−4.713	<0.001	0.001

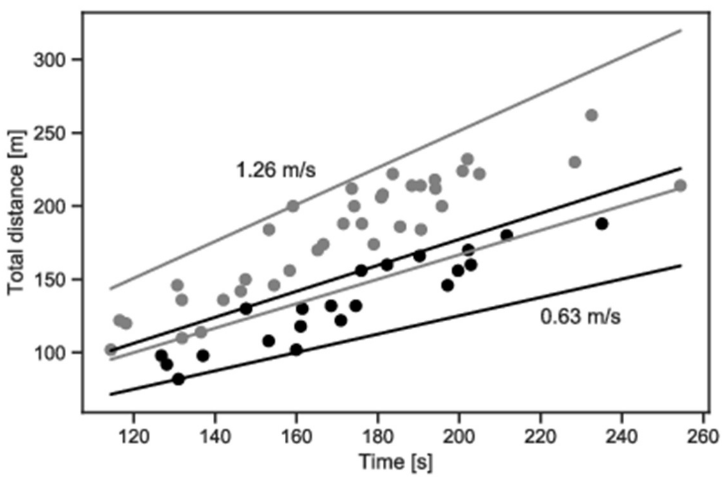

Figure 4. Comparison between CNF and CWT. Evolution of the depth as a function of the dive time with CNF and CWT performance in black and grey respectively. Minimum and maximum speeds are represented as affine functions for both disciplines.

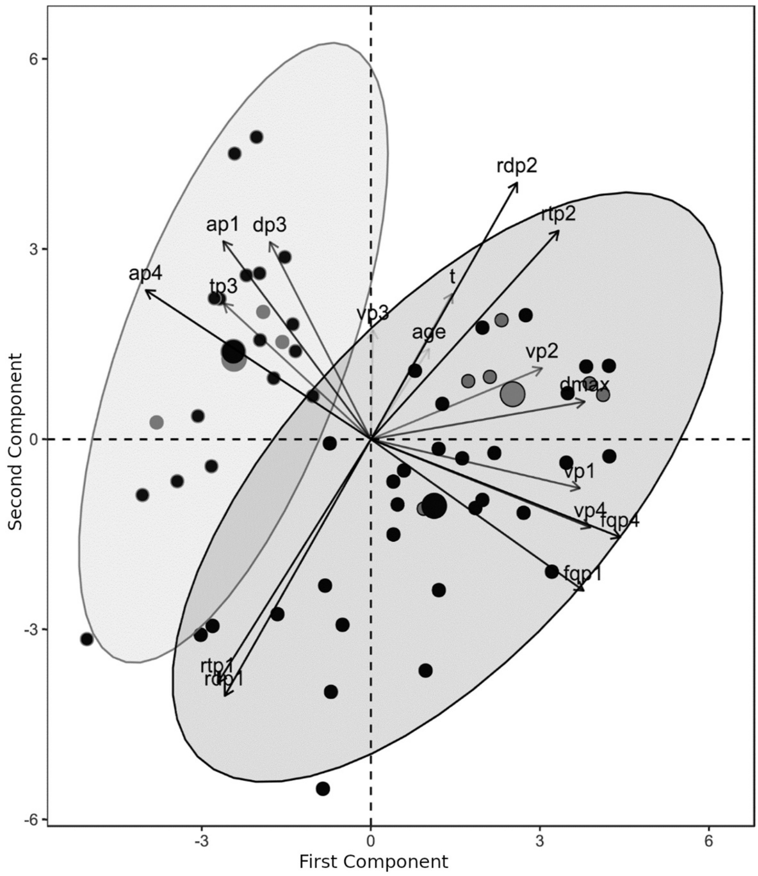

Figure 5. CNF and CWT: Principal Components Analysis (PCA). First two dimensions returned by a PCA with arrows representing the relative contribution of variables. Confidence ellipses are drawn for the CNF group (left) and CWT (right) with valid performances in black and LOC shown in grey. Features labels have a '*pN' suffix for the Nth phase and the radical corresponding to velocities (v*), frequency (fq*), amplitude (ap*), time ratio (rt*) and distance ratio (rd*). Total dive time is noted t, and maximal depth is dmax.

Discussion and implications

For the first time, the technical diving strategies of the BHDs were analysed in the perspective of their possible consequences on the LOC. The main findings are: 1/that the characteristics of strategies have an impact on the occurrence of LOC considering each discipline, CNF and CWT; 2/in CNF, performance ending with LOC are slower than valid performance, especially during the active descent phase, and during the ascent phase for similar distances and time ratios, 3/in CWT, the occurrence of LOC is characterised by quicker active descent phase and longer passive descent phase, leading to longer dives.

In CNF, divers who suffered from LOC achieved lower depths (63 m vs 67 m) in longer time (174 s vs 171 s), meaning that invalid performances are slower than valid ones. Regarding the different phases, divers with LOC are slower in the active descent phase (effect size of 1.08), leading to a faster passive descent (effect size of 0.22) for equivalent distances and time ratios. This result indicates that the BHDs probably have a poorer propulsive technique which leads them to have longer BH times during the propulsive descent phase increasing the BH time. This relative loss of time is also observed during the turn but especially during the ascent. The difference in total BH time is small with BHDs without LOC (+3s) but for shallower depths (−4 m), which may indicate a lower efficiency in their diving technique. Indeed, BHDs with LOC had lower amplitudes (2.17 m vs 2.55 m) for a higher frequency (0.33 vs 0.31), indicating that their motor efficiency was lower. Doing more movement will quickly increase the oxygen consumption, which can lead to LOC. It remains difficult to disentangle the impact of variations of speed on CNF from the buoyancy of the BHDs on the oxygen consumption. We did not have access to the parameters that could cause variations in buoyancy such as the thickness of their wet suit and/or their lung volumes. Nevertheless, we can assume that these high-level athletes are all trained with high volumes and approximately similar wet suits. Although performance is slightly lower in women (56.3 m vs 72.8 m) for shorter diving time (154.6 s vs 181.1 s), women are slower with a smaller amplitude but more frequency. Men and women have indeed different strategies, with men spending around 38% of their descent phases being active while women are active for 59%. This difference can lead to higher oxygen consumption and explains difference in performances between men and women.

In CWT, BHDs with LOC have greater achieved depth (103.5 m vs 88.5 m) in longer dive time (197.3 s vs 166.8 s). With respect to the distinct phases, BHDs ending with an LOC are faster in the active descent phase (effect size of 1.51, +17%), with lower time and distance ratios which indicates that they spend less time on the first active phase. During the second phase, the passive one, LOC have similar speed but with higher distance and time ratios, which indicates that they spend more time gliding. No difference between validated and non-validated performances were found for the turn and the ascent phases. A descent phase with an excessive speed could therefore be predictive of the risk of an LOC in CWT. The occurrence of an LOC would be less a technical problem in CWT due to the lack of difference in amplitude and frequency during all phases. The stress induced by the greatest depth could have resulted in an acceleration in the active phase that allows the BHD to reach its depth but generates additional oxygen consumption, thus increasing the risk of LOC. The role of ballasting and the wet suit thickness, probably less important than in CNF, cannot be ruled out since the single blade allowing greater depths to be reached. In CWT, men and women also have different strategies. Although performance is lower in women (76.2 m vs 103.1 m) for shorter diving times (157.5 s vs 183.4 s), women are faster with more amplitude but similar frequency during the active descent. Women are slower during the second phase, the turn and the ascent. From a technical point of view, they have more amplitude with less frequency. It is difficult to say whether this difference in amplitude explains the differences in performance between men and women, but this seems to be a particular characteristic, although we did not find any difference between men and women concerning the number of LOC.

Interestingly, no differences between distances and time ratios between the two dive disciplines were observed. Even if there is no statistical difference on the number of LOCs', the velocities during phases are different between disciplines. BHDs with LOC in CWT are faster in the first phase and may increase their energy consumption. Compared to valid performances, they are going deeper for a similar activation time of the diving reflex. Interestingly, BHDs ending with a LOC spend lesser distances and less time being active than being passive. This could be interpreted as the fact that they are more efficient. Unlike in CNF, invalid performances seem more efficient at first sight. We suggest that in CWT, strategies may be less important because the main risk factors are depth and dive time, increasing physiological constraints. With only 60% of explained variance provided by the two principal components, the PCA (Figure 5) illustrates the different characteristics of LOC concerning the disciplines. In CWT, two clusters are directly visible and separable thanks to information provided by ratios and performance markers such as depth and dive time. Although this statement does not seem to hold for CNF, at least in a 2D spatial projection. Firstly, genders are mostly distinguishable on the first component which is built upon the achieved depth, the speed, the frequency and the amplitude of the ascent phase. This is coherent with the results of the ANOVA (Tables 1 and 2), showing significant differences. Interestingly, and unlike in CWT, BHDs ending with a LOC are not distinguishable in CNF by the second component, composed mainly of the amplitude of the active descent, and of distance and time ratios. The PCA highlights that LOC is influenced by different factors depending on the discipline, and that distance and time ratios may be the most important LOC factors in CWT.

This study has limitations. As mentioned above, since we do not have data on ballasting, total lung capacity or the wet suit thickness, we cannot precisely determine the influence of these parameters on the speed differences observed in CNF and CWT and their respective roles in the LOC. Nor can we exclude that certain physiological parameters may have played a role in the occurrence of LOC. Several physiological hypotheses are conventionally put forward to explain the LOC during deep dives. The brain requires a constant supply in oxygen, but this supply is impaired by the underwater effort and while this is an inherent factor for the LOC, brain damages may also occur from repeated LOC (Billaut et al., 2018). Under normal circumstances, a diving response to BH protect vital organs (brain and heart) from extreme hypoxia. This diving reflex involves vagally mediated bradycardia, sympathetically mediated peripheral vasoconstriction with an increase in blood pressure, changes in cardiac output and spleen contraction (Dujic & Breskovic, 2012; Ferretti, 2001). The integration of both sympathetic and parasympathetic pathways underlies the ontogenetic origin of the dive responses (Lemaitre et al., 2015). In trained BHDs, dynamic cerebral autoregulation is acutely impaired during maximal BH (Cross et al., 2014), cerebral oxidative metabolism is decreased and a disruption of the blood-brain barrier has also been suggested (Bain et al., 2016, 2018). Thus, all these changes in brain circulation could contribute to increasing the risk of LOC. Pulmonary oedema during deep apnoea is very common (Schipke et al., 2019). It is also common to observe that in the case of LOC, oedema is also present. If pulmonary oedema occurs during deep apnoea, it can complicate gas exchanges and limit the supply of oxygen to the brain. Even if a rapid rate of descent may be a predisposing factor due to potential damages to capillary endothelium (Fitz-Clarke, 2006), the answer seems more complicated as there is a clear relationship between active descent speeds and the discipline (Table 3). This purely descriptive study does not yet allow us to know whether the BHDs who had LOC during these competitions had pulmonary oedema.

Even if this work could not consider all the variables implied in the achievement of a performance, a guideline can be designed for coaches and divers. Coaches should pay more attention to the swimming techniques used by BHDs. Monitoring technical parameters (e.g., amplitude, frequency or speed) either through video analysis or external devices during training sessions is an already used solution in other disciplines like swimming. As LOC is impacted by swimming efficiency, we suggest that BH diving could be made safer through in-depth performance analysis. This would enable coaches to assess diving efficiency and implement appropriate strategies. However, this work does not consider the diver's physiological parameters and equipment. It might be interesting for subsequent research to study interactions between physiology and strategies, or to include ballasting as a strategic parameter.

Conclusion

We had hypothesised that, (i) a high speed and frequency and a low amplitude increase the risk of LOC, and (ii) speed, frequency and amplitude parameters are managed differently in CWT and CNF. We have shown that the strategies are different between CNF and CWT and that certain technical choices increase the risk of LOC. In CNF, to avoid LOC, BHDs should try not to be too slow during the first active descent phase, and especially during the ascent (optimal speeds: 0.85 ± 0.13 m/s and 0.78 ± 0.10 m/s, respectively). In CWT, BHDs should try not to be too fast in the first descent phase of their dive (optimal speed 1.06 ± 0.12 m/s). A deeper exploration of diving performances offers a better comprehension of LOC beside physiological aspects, either to understand the risk factors, enhance training methods, or alert judges and safety divers directly if a typical pattern is detected through live video. This study opens the way to the investigation of technical parameters via video analyses in relation to physiological indices, especially to capture preventive markers of LOC.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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