13621-JSM_N_suppl

The Journal of Sports Medicine and Physical Fitness 2022 mese;62(0):000–000
DOI: 10.23736/S0022-4707.22.13621-2

REVIEW
SECTION

Training methods for maximal static apnea performance: a systematic review and meta-analysis

Danilo A. MASSINI [1, 2, 3], Danilo SCAGGION [2], Thiago P. DE OLIVEIRA [1], Anderson G. MACEDO [1, 3], Tiago A. ALMEIDA [3, 4] *, Dalton M. PESSÔA FILHO [1, 3]

[1]Post-Graduate Program in Human Development and Technology from São Paulo State University (UNESP), Rio Claro, Brazil; [2]University Center of São Paulo State (UNICEP), Rio Claro, São Paulo, Brazil; [3]São Paulo State University (UNESP), Bauru, Brazil; [4]CIPER, Faculty of Human Motricity, University of Lisbon, Lisbon, Portugal

*Corresponding author: Tiago A. Almeida, CIPER, Faculty of Human Motricity, University of Lisbon, 1499-002 Lisbon, Portugal.
E-mail: tiagofalmeida.w@gmail.com

ABSTRACT

INTRODUCTION: Currently, there is an increase in people practicing freediving (FD) both in competition and leisure. As a sports practice, its modalities are grouped into static, dynamic, and constant weight apnea. The aim of this systematic review and meta-analysis (PROSPERO-CRD42021230322) was to identify the training methods used to improve the static apnea time (AT) performance.
EVIDENCE ACQUISITION: Ten training protocols were analyzed from eight studies published until March 09, 2022. The effect size (Hedge's *g*) and its confidence interval ($CI_{95\%}$) were calculated from the AT measured pre- and post-training.
EVIDENCE SYNTHESIS: Three different apnea training methods were verified, the breath-hold (BH) that uses BH exercises, physical training with strength and cardiorespiratory exercises, and cross training that combines BH exercises with physical training. These training methods were applied to 138 participants of both sexes with or without experience in apnea episode or diving practice. In general, the AT improvement showed a large effect after the interventions (g=1.30, $CI_{95\%}$=0.85-1.76, P<0.01).
CONCLUSIONS: All three methods were effective in improving static AT, however from the existing protocols is not possible to recommend an ideal to improve AT and therefore FD performance.

(*Cite this article as*: Massini DA, Scaggion D, De Oliveira TP, Macedo AG, Almeida TA, Pessôa Filho DM. Training methods for maximal static apnea performance: a systematic review and meta-analysis. J Sports Med Phys Fitness 2022;62:000-000. DOI: 10.23736/S0022-4707.22.13621-2)

KEY WORDS: Breath holding; Athletic performance; Exercise; Systematic review; Meta-analysis.

Introduction

Voluntary apnea (*i.e.*, breath holding, BH) enables humans to submerge for performing a freediving (FD) condition. Freediving is an underwater activity initially performed centuries ago to collect pearl shells, seafood, and naval warfare missions.[1, 2] Currently, there is an increasing number of individuals practicing FD in different sports modalities (*e.g.*, competitive freediving, synchronized swimming, target shooting, hockey, and underwater rugby),[3, 4] whether for recreational or competitive purposes.[4, 5] As a requirement for, FD performance, the apnea episode can be improved to achieve greater times or depths underwater with breath-holding.[6-9] In 1992, the International Association for the Development of Freediving (AIDA) was founded, which organizes competitions and keeps a register of world records set in 8 modalities of static, dynamic, and constant weight,[8, 10] as well as supervising all other associated activities.[8] In 2009, the current world record set at static apnea was registered with 11 minutes and 35 seconds,[6, 11] meanwhile, the training effectiveness to improve maximal apnea duration remains indefinitely regarding the method of apnea training (static or dynamic), and planning protocol (underwater or dryland apnea episodes, and types of exercise to combine with apnea) [12,13.] A traditional parameter of static or dynamic apnea training is underwater or dryland apnea time (AT), which is characterized by BH, being sustained for the longest period of time possible.[6] During an apnea episode two phases are observed, separated by a physiological breakpoint (characterized by a sudden increase in the eletromiografic response of the respiratory muscles:[12] 1) the "easy-going" phase determined by physiological factors associated with the accumulation of arterial CO_2, which might be simply understand as the apnea period with no strong impulse for breathing; and 2) the "struggle phase" where involuntary breathing movements (involuntary contraction of the diaphragm) are triggered due to a need to breathe.[13-15] The duration of AT depends on psychological and physiological factors related to O_2 storage, tolerance to hypoxia, and the metabolic rate.[4,5,14,18,19,20], and its improvement occurs due to one or more factors combined, although the physiological mechanisms during an apnea episode are not yet fully understood.[1, 7] Different training methods and protocols have been designed to understand the physiological requirements to improve the apnea episode, both in healthy individuals,[12, 16] and in well trained freedivers.[17-19] However, apnea protocols present a significant variation between studies regarding the training methods, training load parameters (*i.e.*, types of exercises, volume, intensity, recovery, and weekly frequency),[12, 19] and participants' characteristics (*i.e.*, age, sex, apnea experience, and fitness level).[17, 20] Therefore, a systematic review is important to summarize the effect of training methods and, therefore, the effectiveness of training to improve the apnea time performance to support future studies in the selection of protocol to investigate conditioning requirements for FD performance. The questions in the current study were whether there are different training methods used in apnea episode and whether those methods effect the increasing of maximal static apnea duration. To find the responses, this study aimed to: 1) perform a systematic review to identify the training methods applied to apnea episode; and 2) perform a meta-analysis to analyze the effect of training on the improvement of static AT.

Evidence acquisition

Search strategy

This systematic review and meta-analysis were carried out following the recommendations of the Cochrane Handbook for Systematic Reviews of Interventions (version 5.1.0), and its writing followed the checklist Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).[21] This systematic review was registered with the International Prospective Register of Systematic Reviews (PROSPERO - CRD 42021230322) on February 18, 2021.

Literature search

The search for high sensitivity without a time limit was elaborated according to the PICOS strategy:

- participants – trained and apnea non-trained freedivers, healthy adults aged between 18 and 45 years being in favorable biological conditions for developing and improving sports performance.
- intervention – studies that investigate the effect of apnea training regardless of duration, intensity, or type of exercise will be considered for inclusion.
- comparator – the primary comparison of interest is the pre-post difference in static apnea time after training, as a result of each study protocol.
- outcome – the main result of interest is the static apnea time in response to a training protocol.
- study design – any study design that includes measurements of static AT before and after training will be considered for inclusion. These include randomised and nonrandomized clinical trials, including cross-over trials and pre-post single group studies. Our justification for including these different types of studies is based on: 1) our desire to be as inclusive as possible; 2) identifying whether the results are associated with these different types of studies; and 3) providing direction for future primary studies in what it concerns the design of studies aimed at examining the effects of training on static AT.

The following descriptors were applied: "freediving" AND "healthy" AND "apnea training" AND "breath-holding" OR "apneic time" NOT "sleep apnea" with the filters: "full text," "humans," "English," "adult: 19-45 years." The search strategy was submitted to a peer review by an information scientist using the Evaluation Form of the Peer Review Guidelines for Electronic Search Strategy (PRESS)[22] and is available in Supplementary Digital Material 1: Supplementary Text File I, II, Supplementary Figure 1-5). The sensitivity of the descriptors was assessed in the location of the article by Shagatay *et al*.[12] Computerized searches were subsequently performed in the PubMed, ScienceDirect, Cochrane Library, SPORTDiscuss, Web of Science, Embase, Scopus, CINAHL, LILACS, PEDro, and SciELO databases for studies published until December 11, 2020. In addition to the studies found, a new period was considered until March 09, 2022. Gray Literature searches (dissertations, thesis, and Conference Proceedings) were performed in the OATD (Open Access Theses and Dissertations), OpenDissertations, PubMed, ScienceDirect, Embase, SPORTDiscuss, and Web of Science databases. To add other relevant titles, manual searches were performed on the references of the eligible articles and their citations in the PubMed, Scopus, and GoogleScholar (Google LLC., Mountain View, CA, USA) databases. Finally, attempts were made to contact the authors of the selected articles via email to request further relevant information. For studies which presented only chart information, values were get through specialized software (WebPlotDigitizer version 4.5, Pacifica, CA, USA). The searching process was performed independently by two authors (DAM and TPO) to avoid any selection bias. After their completion, the authors compared the lists of included and excluded studies, and the observed discrepancies were analyzed through discussion and agreement with a third author (DMPF).

Study selection criteria

Studies that measured static AT pre- and post-training were included, independently of the environment where training was planned (*i.e.*, underwater or dryland). The inclusion criteria adopted were: 1) complete studies carried out in healthy humans aged between 18 and 45 years; and 2) peer-reviewed and published in English without a time limit. The exclusion criteria were: 1) studies with clinical populations, which used dietary supplements or ergogenic resources that alter blood flow; 2) literature reviews (narrative, systematic, and meta-analysis reviews); and 3) studies with low methodological quality.

Data extraction

The data were extracted by two authors (AGM and TAFA) using a pre-pilot spreadsheet and verified independently by a third author (DAM) from the review team. The following data were extracted: 1) name of the authors; 2) year of publication; 3) characteristics of the population (sample size, sex, age, height. and body mass); 4) training method; 5) training load parameters (exercises, volume, intensity, recovery, weekly frequency, and duration of the intervention); and 6) pre- and post-training AT.

Determination of methodological quality

This was carried out by two independent authors (DAM and DS), and the discrepancies observed were analyzed by a third author (DMPF) using the "Tool for the assessment of Study qualiTy and reporting in EXercise" (TESTEX) checklist,[23] which gives the study 1 point if the criterion is satisfied, or 0 points if the criteria are not satisfied. The checklist contains two sections that refer to quality (items 1 – 5) and study report (items 6-12); items 6 and 8 have three and two questions respectively, giving a total of 15 points. Based on the summarized scores, the studies were classified as "excellent quality" (12-15 points), "good quality" (9-11 points), "fair quality" (6-8 points), or "low quality" (<6 points) (Table I).[28]

Statistical analysis

The statistical analysis was performed by one author (DAM) and reviewed by a second one (DMPF). For these estimates, the sample size, mean values, and standard deviation of the AT pre- and post-training for each condition (training methods) of each study included in the meta-analysis were used. The relative effects of training (Δ%) were provided in percentages according to equation 1.

$$\Delta\% = [(\bar{X}_{post} - \bar{X}_{pre}) / \bar{X}_{pre}] \cdot 100$$

where "Δ%" is the training effect in percentage, "$\bar{X}_{pre}$" is the mean static AT pre-training and "$\bar{X}_{post}$" is the mean static AT post-training. The magnitude of the result after each training protocol was determined by means of the standardized differences adjusted by the Hedge's *g* and 95% confidence interval ($CI_{95\%}$) due to the small sample size (N.<30) of the included studies.[29] Study estimates were combined within the meta-analysis using a random-effects model and presented as forest plot graphics. The inconsistency was verified using the results of the meta-analysis and was based on the visual inspection of the Hedge's *g* estimates, with $CI_{95\%}$ overlapped or not, as well as on statistical tests for heterogeneity (I^2) determined by the combination of the Cochrane Q test with the Higgins Test.[30] Its value was classified as: $0<I^2\leq 25\%$ indicating non-heterogeneity, $25<I^2\leq 50\%$ indicating low heterogeneity, $50<I^2\leq 75\%$ indicating moderate heterogeneity, and $I^2>75\%$ indicating high heterogeneity between studies.[31] The analysis of publication bias (Egger's Test) was not evaluated due to the small number (N.<10) of included studies,[32-34] as well as an additional subgroup and meta-regression analyses. The effect size for Hedge's *g* was categorized as: ≤0.19=trivial, 0.20-0.59=small, 0.60-1.19=moderate, and ≥1.20=large.[35] All analyses were performed using software R (version 4.0.3) and using the RStudio environment (version 1.3.1093; R Foundation for Statistical Computing, Vienna, Austria) with the meta[36] and metafor[37] packages. For all statistical procedures, a significance index of α=0.05 was adopted.

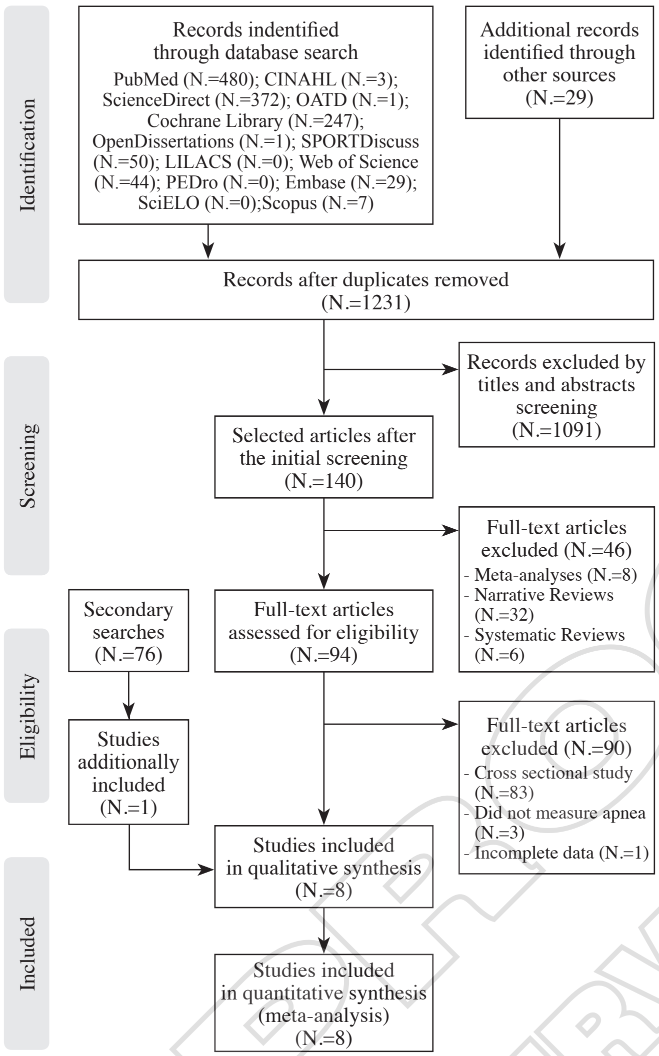

Figure 1.—Prism flow diagram of the search process.

Evidence synthesis

Figure 1 presents the flowchart for all stages of the systematic review and meta-analysis, and Table II, III, IV[7, 12, 17, 20, 24-27] present the main characteristics of the eight included studies,[7, 12, 17, 20, 24-27] from the year of 1984 until 2013, from 2014 until January of 2019 and from February of 2019 until 2022, respectively. Six studies were carried out in Europe and two in the USA. These studies enrolled 138 participants (74% men and 26% women) aged 18 to 45 years. As for FD experience, only 19 (14% of participants) had two years of experience, and all were men. As for the ten training protocols included, three different methods were observed. The BH method was used in eight of the ten protocols, planned with static or dynamic BH in underwater and dryland exercise condition. The cross training (CT) and physical training (PT) were each one included in two and one protocols, respectively. The intensities used were maximum and submaximal (BH: 50% of dryland apnea, PT: 50% of maximal oxygen uptake), with recoveries varying between 50% of dryland apnea up to 10 minutes in duration. The training sessions lasted between 7-60 minutes, weekly frequency between three to seven days, with interventions lasting five days to 22 weeks. Finally, there was an increase in static AT between 15-62% (Figure 1). Table I[7, 12, 17, 20, 24-27] presents the methodological quality of the results for each criterion on the TESTEX Scale for all included studies. Four studies showed good methodological quality[12, 17, 24, 27], and others four studies were reasonable.[7, 20, 25, 26] Figure 2[7, 12, 17, 20, 24-27] shows the meta-analysis including eight studies and the ten training protocols. These studies combined by the random-effect model showed a significant effect on the static AT of each training protocol (g=1.30,

Table I.—*Methodological quality using the TESTEX assessment.*

Study	Criterion							
	Study quality					Study reporting		
	Eligibility criteria specified	Randomization specified	Allocation concealment	Groups similar at baseline	Blinding of assessor	Study reporting: Participants adherence >85%	Adverse events	Exercise adherence
	1	2	3	4	5	6a	6b	6c
Hentsch *et al.*[24]	0	0	0	1	0	1	0	1
Schagatay *et al.*[12]	0	0	0	1	0	1	0	1
Joulia *et al.*[25]	0	0	0	0	0	1	0	1
Engan *et al.*[20]	0	0	0	0	0	1	0	1
Fernandez *et al.*[17]	0	0	0	1	0	1	0	1
Stanford[26]	0	0	0	0	0	1	0	1
Bouten *et al.*[7]	1	0	0	0	0	0	0	1
Bouten *et al.*[27]	1	0	0	1	0	1	0	1

TABLE II.—*Earlier studies on apnea training method: the eligible researchers from 1984 to 2013.*

Study	Participants						Apnea Training protocol				Apnea time		
	Method	Sex	Free diver	Age (years)	Hight (meters)	Body mass (kg)	Exercises modalities	Description	Weekly frequency	Duration	Pre (s)	Post (s)	Δ (%)
Hentsch *et al.*[24]	Breath-holding	10 M, 11 W	No	21-45			Breath-holding	2 maximal breath-holds with a 3 min recovery break	5	5 days	33±20	53±25	62
Schagatay *et al.*[12]	Breath-holding	5 M, 4 W	No	25			Breath-holding	5 maximal effort apneas with 2 min intervals every day for 2 weeks	4	2 weeks	107±11	123±9	15
	Physical Training	13 M, 11 W	No	26			Running, jumping and gymnastics involving large muscle groups	Low intensity exercises (50-60% $\dot{V}O_{2max}$) combined with high intensity (70-80%$\dot{V}O_{2max}$) work-intervals of about 3 min repeated 4 times per workout, for a total time of 60 min	3	8 weeks	74±7	88±10	19
Joulia *et al.*[25]	Cross Training	8 M	No	22.6±4.6		72.5±6.6	Breath-holding and cycling	Repetitions of 20 s of breath-holding separated by 40 s of breathing room air during a 1 h steady state cycling exercise at 30%VO_{2max}	3	3 months	104±14	155±15	49
Engan *et al.* [23]	Breath-holding	6 M 4W	No	25±6	1.75±0.1	72±9	Breath-holding	10 maximal apneas trials in seated or supine position, divided in two series of 5 apneas with 2 min rest interval, with 10 min rest between series	6	12 days	157±50	200±53	27

M: men; W: women; rep: repetitions; s: seconds; HIIT: high intensity interval training.

$CI_{95\%}$=0.85-1.76, P<0.01 [large]). The inconsistency analysis by visual inspection of the overlapping $CI_{95\%}$ combined with statistical tests present low heterogeneity (I^2=41.6%, $CI_{95\%}$=0.0-72.1%; $Q_{[9]}$=15.4, P=0.08). The present study evidenced the effect of apnea training on static AT performed in underwater and dryland conditions. Eight studies were eligible and classified into the fair level for methodological quality. The ten training protocols combined showed homogeneity and a large effect on static AT.[30, 34] In this way, apnea training was considered effective to improve AT performance. Regarding the populations included in the studies, no study included par-

Criterion: Study reporting							Total	
Intention-to-treat analysis	Between-group statistical comparisons reported: Primary outcome	Between-group statistical comparisons reported: Secondary outcome	Point and variability measures	Activity monitoring in control groups	Relative exercise intensity remained constant	Exercise volume and energy expenditure	Scores	Rating
7	8a	8b	9	10	11	12		
1	1	1	1	0	1	1	9	Good quality
1	1	1	1	1	1	1	10	Good quality
1	0	0	1	0	1	1	6	Fair quality
1	0	0	1	0	1	1	6	Fair quality
1	1	1	1	1	1	1	10	Good quality
1	0	0	1	0	1	1	6	Fair quality
1	0	0	1	0	1	1	6	Fair quality
1	1	1	1	1	1	1	11	Good quality

Table III.—*Later studies on apnea training methods, encompassing the time period from 2014 to the beginning of 2019.*

Study	Participants						Apnea Training protocol				Apnea time		
	Method	Sex	Free diver	Age (years)	Hight (meters)	Body mass (kg)	Exercises modalities	Description	Weekly frequency	Duration	Pre (s)	Post (s)	Δ (%)
Fernandez *et al.*[17]	Breath-holding	9 M	Yes	34.3±7.8	1.79±0.1	74.4±3.3	Breath-holding	Specific hypoxic training in dynamic – first and second session: 40 reps of 25 m dynamic apneas to maximum individual underwater swimming speed with 20 s of recovery each 25 m	2 1	22 weeks	182±55	250±33	37
	Cross Training	10 M	Yes	36.4±0.4	1.76±0.1	75.3±12.8	Calisthenic exercises, swimming, and dynamic and static specific hypoxic training	Specific hypoxic training in static	1		185±43	249±43	35
								Third session: 3 maximal static apneas with 10 min of full recovery between each apnea.					
								First session: 15 min with a dryland strength circuit of 10 calisthenic exercises - squat, pull-up, push-up, squat, pull-up, push-up, squat, pull-up, push-up, and squat- with 50 reps and 10 s of recovery. This was followed by swimming training in crawl, alternating each week between 45 min of continuous swimming training (14 RPE) and HIIT (20 RPE). Regarding HIIT, volume and density were 3 sets of 10 reps of 25 m with 20 s of recovery					
								Second session: participants performed a specific hypoxic training in dynamic	1				
								Third session: participants conducted a specific hypoxic training in static.	1				

M: men; W: women; rep: repetitions; s: seconds; HIIT: high intensity interval training.

Table IV.—*The newest studies eligible on the search for the apnea training methods.*

Study	Participants						Apnea training protocol				Apnea time		
	Method	Sex	Free diver	Age (years)	Hight (meters)	Body mass (kg)	Exercises modalities	Description	Weekly frequency	Duration	Pre (s)	Post (s)	Δ (%)
Stanford[26]	Breath-holding	9 M, 6 W	No	22.7±4.8	1.74±0.1	72.4±13.2	Breath-holding	8 submaximal reps (50% dryland apnea) with passive recovery between 80-45% dryland apnea (5% reduction per day)	7	12 days	67±25	97±45	45
Bouten *et al.*[7]	Breath-holding	10 M	No	18-30			Breath-holding	5 static breath-hold apneas in a seated position separated by 2 min rest interval: first 4 bouts at 80% of the pre-test' maximal apneic duration and last bout at maximal apnea. Target times adjusted after 4 weeks of training	7	8 weeks	116±15	178±45	53
Bouten *et al.*[27]	Breath-holding	22 M	No	27.1±3.5	1.80±0.1	72.5±8.3	Breath-holding	5 maximal static breath-holds with 30 s rest intervals	7	6 weeks	118±54	155±53	31

M: men; W: women; rep: repetitions; s: seconds; HIIT: high intensity interval training.

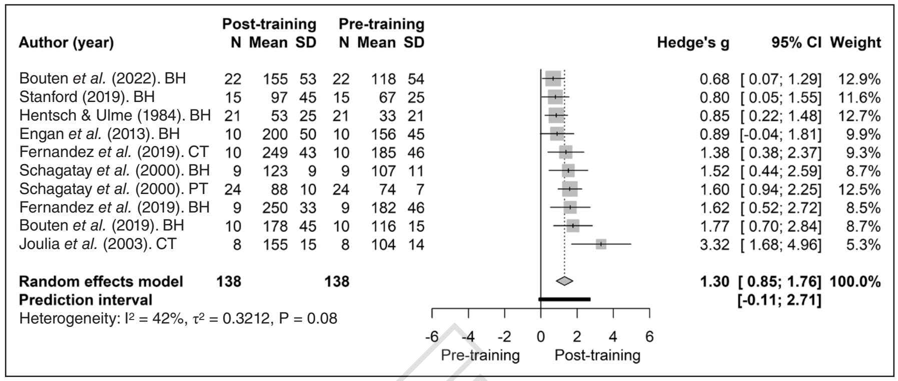

Figure 2.—The forest plot for the effects of training on static AT performed at both underwater and dryland conditions.
The ordinate axis denotes Hedge's *g* (ES) with symbols denoting the 95% confidence interval (95% CI).

ticipants aged ≤17 years, which is recommended to avoid the effect of the biological maturation state on the tolerance of the central nervous system to the apnea duration.[8] The studies employing healthy individuals did not include the level of experience, except for the study of Fernandez *et al*.,[17] which included freedivers athletes (two or more years of practice), despite of AT score of these freedivers does not allow them to be classified as elite athletes, as the performance in FD is less than five minutes.[11, 16, 25] The fact that none of the included studies analyzed elite athletes precludes the extrapolation of the results from this systematic review and meta-analysis to this population. Likewise, the current results cannot be applied to females since none of the studies included women separately[12, 24, 36] or included both sexes into a single group. The different training methods (BH, PT, and CT) enable similar adaptations regarding several factors such as psychological, as the increase of tolerance during an apnea episode,[7, 12, 17, 20, 24, 26, 27] pulmonary, as the increase of vital capacity;[3, 17, 19, 38] respiratory, as the control of metaboloreflexes;[12, 19, 25, 26] cardiological, as the bradycardia and peripheral vasoconstriction;[3, 7, 19, 38] and hematological, as the hypervolemia, increased concentration of erythropoietin and haematocrit.[3, 7, 12, 39] Therefore, training protocols are designed to match goals such as: CT and HIIT (high-intensity interval training) which contribute to the mechanical efficiency of swimming underwater, which is plausible for dynamic apnea;[16, 17] PT which contributes to the reduction of blood lactate accumulation and the improvement of aerobic energy supply during an apnea episode,[12,14,22,29]; and BH which specifically induces adaptive mechanisms to protect anoxia and reduce O_2 consumption.[8] Regarding the different training methods included in the protocols, the static BH was used in the studies by Hentsch *et al*.,[24] Schagatay *et al*.,[12] Fernandez *et al*.,[17] Engan *et al*.,[20] and Bouten *et al*.,[27] being performed at maximum intensity, repeated two to ten times with recovery lasting two to ten minutes in each training session. Exercises at submaximal exertion rates in the BH method were designed in the study of Stanford,[26, 40] which differed from other studies with regard the short time of rest between the eight efforts made, and in the study of Bouten *et al*.,[7] with five consecutive BH apneas, four at 80% of the maximal apnea duration and the last one at maximal apnea. Dynamic apnea exercises were designed in the Fernandez *et al*.[17] and Joulia *et al*.[25] studies, with exercise sets of 25 meters, performed at maximum speed and with 20 seconds of rest between the sets, or cycling at 30% of maximal oxygen uptake while the subjects interspersed 20 seconds of breath holding with 40 seconds breathing the room air. Aerobic exercises such as cycling and running, have also been applied, as in the Schagatay *et al*.[12] study, which planned high-intensity trials (70-80% $\dot{V}O_2$max) with active recovery intervals in low-intensity trials (50-60% $\dot{V}O_2$max), as well as callisthenic exercises followed by HIIT which was applied to the increase of muscle strength for swimming performance.[17] The variety of such different exercises being applied, illustrates the attempts to match the specific requirements for the competitive demands (static or dynamic apnea) that freedivers undergo.[12, 17] The durations of the training protocols are varied, resulting in different morphological and physiological adaptations being observed after each intervention.[39, 41] Furthermore, apnea time improves as an acute effect of breath holding training, which is therefore recognized as a short-term adjustment from repeated breath holding trials in a planning session no longer than 10 minutes.[37, 42, 43] The physiological mechanism underlying this adjustment is probably the slowing of oxygen content reduction in blood as an effect of increased blood flow to central regional of body and reduction of cardiac output.[42, 44] Subsequently, de Bruijn *et al*.[45] and Richardson *et al*.[46] reported an increase in the concentration of erythropoietin and hemoglobin in response to spleen contraction. After two weeks of BH training, Engan *et al*.[20] found a reduction in O_2 desaturation due to bradycardia. After eight weeks, Bouten *et al*.[7] reported an increase in the spleen volume. Above all, the different adaptations in response to the duration of interventions are also dependent on training loads, which still does not have a consensus on the ideal combination of these variables for the elaboration of training,[20] as well as whether their results are due to individual predispositions[7, 47] or genetic variations.[7, 48] Methodological concerns are related to the not large number of studies included, which prevent subgroup meta-regression analyses from investigating the effects of the different training methods, training load parameters, fitness level, and sex, as well as improvement of others variables of dynamic apnea performance (*e.g.*, underwater distance, which has been reported to improve ~48% after a short-planning of dynamic apnea).[49] However, the number of training protocols included does not constrain confidence in the result of this meta-analysis, as suggested by Grgic *et al*.[33] Thus, future studies should analyse: 1) the effects of the different apnea training methods; 2) their respective training loads (types of exercises, volume, intensity, recovery, and weekly frequency); 3) temporal effect of the intervention (short, medium, and long term); 4) effect of sex and 5) fitness level (untrained, trained, and elite) to achieve the ideal stimulus for the desired adaptations.

Conclusions

In conclusion, this study observed that different apnea training methods improved the apnea time performance, despite few studies being found demonstrating the effect of training methods on underwater and dryland static AT performance. However, a recommendation of an effective training protocol is still a challenge since no uniformity in the training planning was observed between protocols. The training methods enabling improvement of static apnea are: 1) breath-hold; 2) physical training with dryland exercises; and 3) cross training, and physical training with breath-hold exercises. Therefore, this systematic review and meta-analysis revealed that the training methods had significant effect on underwater and dryland AT performance. Undoubtedly, the generalization of the results is limited to the age groups and fitness level reported in the studies revised. It is also important to note that the number of studies is not per se a constraint for a consensus regarding training protocol effectiveness for the improvement of the static AT performance, since the effect was large and are consistent (*i.e.*, low heterogeneity).

References

1. Eichhorn L, Erdfelder F, Kessler F, Dolscheid-Pommerich RC, Zur B, Hoffmann U, *et al.* Influence of Apnea-induced Hypoxia on Catecholamine Release and Cardiovascular Dynamics. Int J Sports Med 2017;38:85–91.

2. Moir ME, Klassen SA, Al-Khazraji BK, Woehrle E, Smith SO, Matushewski BJ, *et al.* Impaired dynamic cerebral autoregulation in trained breath-hold divers. J Appl Physiol 2019;126:1694–700.

3. Bain AR, Drvis I, Dujic Z, MacLeod DB, Ainslie PN. Physiology of static breath holding in elite apneists. Exp Physiol 2018;103:635–51.

4. RodrÍguez-Zamora L, Engan HK, Lodin-Sundström A, Schagatay F, Iglesias X, Rodríguez FA, *et al.* Blood lactate accumulation during competitive freediving and synchronized swimming. Undersea Hyperb Med 2018;45:55–63.

5. Steinberg F, Doppelmayr M. Neurocognitive Markers During Prolonged Breath-Holding in Freedivers: An Event-Related EEG Study. Front Physiol 2019;10:69.

6. Billaut F, Gueit P, Faure S, Costalat G, Lemaître F. Do elite breath-hold divers suffer from mild short-term memory impairments? Appl Physiol Nutr Metab 2018;43:247–51.

7. Bouten J, Caen K, Stautemas J, Lefevere F, Derave W, Lootens L, *et al.* Eight weeks of static apnea training increases spleen volume but not acute spleen contraction. Respir Physiol Neurobiol 2019;266:144–9.

8. Ostrowski A, Strzała M, Stanula A, Juszkiewicz M, Pilch W, Maszczyk A. The role of training in the development of adaptive mechanisms in freedivers. J Hum Kinet 2012;32:197–210.

9. Overgaard K, Friis S, Pedersen RB, Lykkeboe G. Influence of lung volume, glossopharyngeal inhalation and P(ET) O2 and P(ET) CO2 on apnea performance in trained breath-hold divers. Eur J Appl Physiol 2006;97:158–64.

10. Breskovic T, Ivancev V, Banic I, Jordan J, Dujic Z. Peripheral chemoreflex sensitivity and sympathetic nerve activity are normal in apnea divers during training season. Auton Neurosci 2010;154:42–7.

11. Bouten J, Bourgois JG, Boone J. Hold your breath: peripheral and cerebral oxygenation during dry static apnea. Eur J Appl Physiol 2020;120:2213–22.

12. Schagatay E, van Kampen M, Emanuelsson S, Holm B. Effects of physical and apnea training on apneic time and the diving response in humans. Eur J Appl Physiol 2000;82:161–9.

13. Andersson JP, Schagatay E. Repeated apneas do not affect the hypercapnic ventilatory response in the short term. Eur J Appl Physiol 2009;105:569–74.

14. Guaraldi P, Serra M, Barletta G, Pierangeli G, Terlizzi R, Calandra-Buonaura G, *et al.* Cardiovascular changes during maximal breath-holding in elite divers. Clin Auton Res 2009;19:363–6.

15. Taboni A, Fagoni N, Moia C, Vinetti G, Ferretti G. Gas exchange and cardiovascular responses during breath-holding in divers. Respir Physiol Neurobiol 2019;267:27–34.

16. Joulia F, Steinberg JG, Wolff F, Gavarry O, Jammes Y. Reduced oxidative stress and blood lactic acidosis in trained breath-hold human divers. Respir Physiol Neurobiol 2002;133:121–30.

17. Fernandez FA, Martin-Martin R, García-Camacha I, Juarez D, Fidel P, González-Ravé JM. Medium term effects of physical conditioning on breath-hold diving performance. Respir Physiol Neurobiol 2019;259:70–4.

18. Tocco F, Crisafulli A, Melis F, Porru C, Pittau G, Milia R, *et al.*

Cardiovascular adjustments in breath-hold diving: comparison between divers and non-divers in simulated dynamic apnoea. Eur J Appl Physiol 2012;112:543–54.

19. de Asís-Fernández F, Del Corral T, López-de-Uralde-Villanueva I. Effects of inspiratory muscle training versus high intensity interval training on the recovery capacity after a maximal dynamic apnoea in breath-hold divers. A randomised crossover trial. Diving Hyperb Med 2020;50:318–24.

20. Engan H, Richardson M, Lodin-Sundström A, van Beekvelt M, Schagatay E. Effects of two weeks of daily apnea training on diving response, spleen contraction, and erythropoiesis in novel subjects. Scand J Med Sci Sports 2013;23:340–8.

21. Moher D, Shamseer L, Clarke M, Ghersi D, Liberati A, Petticrew M, *et al.*; PRISMA-P Group. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst Rev 2015;4:1.

22. McGowan J, Sampson M, Salzwedel DM, Cogo E, Foerster V, Lefebvre C. PRESS Peer Review of Electronic Search Strategies: 2015 Guideline Statement. J Clin Epidemiol 2016;75:40–6.

23. Smart NA, Waldron M, Ismail H, Giallauria F, Vigorito C, Cornelissen V, *et al.* Validation of a new tool for the assessment of study quality and reporting in exercise training studies: TESTEX. Int J Evid-Based Healthc 2015;13:9–18.

24. Hentsch U, Ulmer HV. Trainability of underwater breath-holding time. Int J Sports Med 1984;5:343–7.

25. Joulia F, Steinberg JG, Faucher M, Jamin T, Ulmer C, Kipson N, *et al.* Breath-hold training of humans reduces oxidative stress and blood acidosis after static and dynamic apnea. Respir Physiol Neurobiol 2003;137:19–27.

26. Stanford N. Apnea Training and Physical Characteristics: Enhancement of the Dive Response, Apneic Time, and Recovery. Boise, ID: Boise State University Theses and Dissertations; 2019.

27. Bouten J, Debusschere J, Lootens L, Declercq L, Van Eenoo P, Boone J, *et al.* Six weeks of static apnea training does not affect Hbmass and exercise performance. J Appl Physiol 2022;132:673–81.

28. Nunes JP, Grgic J, Cunha PM, Ribeiro AS, Schoenfeld BJ, de Salles BF, *et al.* What influence does resistance exercise order have on muscular strength gains and muscle hypertrophy? A systematic review and meta-analysis. Eur J Sport Sci 2021;21:149–57.

29. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. Front Psychol 2013;4:863.

30. Higgins JP, Thompson SG. Quantifying heterogeneity in a meta-analysis. Stat Med 2002;21:1539–58.

31. Su L, Fu J, Sun S, Zhao G, Cheng W, Dou C, *et al.* Effects of HIIT and MICT on cardiovascular risk factors in adults with overweight and/or obesity: A meta-analysis. PLoS One 2019;14:e0210644.

32. Egger M, Davey Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. BMJ 1997;315:629–34.

33. Grgic J, Diaz-Lara FJ, Coso JD, Duncan MJ, Tallis J, Pickering C, *et al.* The Effects of Caffeine Ingestion on Measures of Rowing Performance: A Systematic Review and Meta-Analysis. Nutrients 2020;12:434.

34. Jones MD, Wewege MA, Hackett DA, Keogh JW, Hagstrom AD. Sex Differences in Adaptations in Muscle Strength and Size Following Resistance Training in Older Adults: A Systematic Review and Meta-analysis. Sports Med 2021;51:503–17.

35. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc 2009;41:3–13.

36. Balduzzi S, Rücker G, Schwarzer G. How to perform a meta-analysis with R: a practical tutorial. Evid Based Ment Health 2019;22:153–60.

37. Viechtbauer W. Conducting meta-analyses in R with the metafor package. J Stat Softw 2010;36:1–48.

38. Gangwar V, John N, Verma M, John J, Gangwar R, Jasrotia RB. Impact of moderate and high intensity exercise on lung volumes, lung capacities, and breath holding time. International Journal of Health and Clinical Research 2020;3:67–73.

39. Lemaître F, Joulia F, Chollet D. Apnea: a new training method in sport? Med Hypotheses 2010;74:413–5.

40. Barwood MJ, Datta AK, Thelwell RC, Tipton MJ. Breath-hold time during cold water immersion: effects of habituation with psychological training. Aviat Space Environ Med 2007;78:1029–34.

41. Costalat G, Coquart J, Castres I, Joulia F, Sirost O, Clua E, *et al.* The oxygen-conserving potential of the diving response: A kinetic-based analysis. J Sports Sci 2017;35:678–87.

42. Schagatay E, van Kampen M, Andersson J. Effects of repeated apneas on apneic time and diving response in non-divers. Undersea Hyperb Med 1999;26:143–9.

43. Andersson JP, Linér MH, Fredsted A, Schagatay EK. Cardiovascular and respiratory responses to apneas with and without face immersion in exercising humans. J Appl Physiol 2004;96:1005–10.

44. Delahoche J, Delapille P, Lemaître F, Verin E, Tourny-Chollet C. Arterial oxygen saturation and heart rate variation during breath-holding: comparison between breath-hold divers and controls. Int J Sports Med 2005;26:177–81.

45. de Bruijn R, Richardson M, Schagatay E. Increased erythropoietin concentration after repeated apneas in humans. Eur J Appl Physiol 2008;102:609–13.

46. Richardson MX, de Bruijn R, Schagatay E. Hypoxia augments apnea-induced increase in hemoglobin concentration and hematocrit. Eur J Appl Physiol 2009;105:63–8.

47. Schagatay E, Richardson MX, Lodin-Sundström A. Size matters: spleen and lung volumes predict performance in human apneic divers. Front Physiol 2012;3:173.

48. Ilardo MA, Moltke I, Korneliussen TS, Cheng J, Stern AJ, Racimo F, *et al.* Physiological and Genetic Adaptations to Diving in Sea Nomads. Cell 2018;173:569–580.e15.

49. Elia A, Barlow MJ, Wilson OJ, O'Hara JP. Six weeks of dynamic apnoeic training stimulates erythropoiesis but does not increase splenic volume. Eur J Appl Physiol 2021;121:827–38.

Conflicts of interest.—Anderson G. Macedo, Tiago A. Almeida and Dalton M. Pessôa Filho received a research grant from the Brazilian Federal Agency for Support and Evaluation of Graduate Education (CAPES), in the scope of the Program CAPES-PrInt, process number 88887.310463/2018-00, mobility number 88887.580265/2020-00. Anderson G. Macedo received a research grant from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brazil (CAPES – finance code 001).

Authors' contributions.—All authors contributed to the manuscript draft; Danilo Massini, Danilo Scaggion, Thiago de Oliveira and Dalton Pessôa Filho have given substantial contributions to the study design and to data collection; Danilo Massini, Tiago Almeida and Anderson Macedo contributed to the data extraction; Danilo Massini, Danilo Scaggion and Dalton Pessôa Filho contributed to the methodological quality and risk of bias assessment, and to the performance of the statistical analysis; Danilo Massini, Anderson Macedo, Tiago Almeida, and Dalton Pessôa Filho contributed to data interpretation and manuscript critical revision for important intellectual content. All authors read and approved the final version of the manuscript.

History.—Article first published online: April 19, 2022. - Manuscript accepted: April 12, 2022. - Manuscript revised: March 30, 2022. - Manuscript received: November 30, 2021.

Supplementary data.—For supplementary materials, please see the HTML version of this article at www.minervamedica.it