Available online at www.sciencedirect.com

ScienceDirect

Journal of Sport and Health Science 4 (2015) 357–363

www.jshs.org.cn

Review

The effects of fluid loss on physical performance: A critical review

Andrew Carlton, Robin Marc Orr *

Faculty of Health Sciences and Medicine, Bond Institute of Health and Sport, Gold Coast, Queensland 4226, Australia

Received 21 March 2014; revised 27 May 2014; accepted 17 September 2014
Available online 3 February 2015

Abstract

Purpose: The purpose of this review was to critically analyse the current evidence investigating the effect of an athlete's hydration status on physical performance.
Methods: A literature search of multiple databases was used to identify studies that met the inclusion criteria for this review. The included studies were then critically appraised using the Downs and Black protocol.
Results: Nine articles were found to meet the inclusion criteria, with an average score of 79% for methodological quality representative of a "high" standard of research.
Conclusion: The evidence suggests that dehydration has a negative impact on physical performance for activities lasting more than 30 s in duration. However dehydration was found to have no significant impact on physical performance for activities lasting less than 15 s in duration.

Keywords: Athlete; Dehydration; Euhydration; Hydration; Performance

1. Introduction

The idea that bodily fluid loss, in the form of dehydration, impairs an athlete's physical performance is not new. In 1955, Buskirk et al.[1] discussed the negative impact dehydration had on VO_{2max}. Since this research, evidence supporting dehydration related impairments in aerobic performance,[2] anaerobic performance,[3,4] and cognitive performance,[5] have been published, as have incidents whereby athlete dehydration has led to the risk of fatality.[6]

A state of dehydration can be induced through physical activity (PA).[7] However, the level of dehydration induced can be dependent upon a number of variables including the type, intensity, and duration of the PA and the temperature and humidity of the environment.[8] Hence studies have been undertaken to investigate the impact that PA has on dehydration, and conversely the impact that different levels of dehydration have on physical performance. The intent of these studies was to better understand the need for an athlete to maintain a state of euhydration (absence of dehydration).[8] As an athlete's performance essentially requires a degree of PA and PA is known to potentially induce a state of dehydration and reduce an athlete's performance, an understanding of the relationship between PA and hydration status is important if a coach wishes to optimize their athlete's performance and prevent a potentially life threatening incidence. On this basis, the purpose of this review was to critically analyse the current literature investigating the effect of dehydration on physical performance.

2. Methods

A two-layered search strategy was utilized for the review. Firstly, a comprehensive search of online databases including PubMed, CINHAL, Web of Science, SPORTSDiscus, and EBSCO: Academic Search Complete was completed. The search terms, "fluid loss" or "exercise induced dehydration" and "performance" and "physical task" or "exercise" and filters used for the searches of these databases are detailed in Table 1. All articles noted from the original database search were checked for duplicates, and these were subsequently removed. Secondly, the reference lists of articles from the database search that were retrieved in full text were cross-checked against the list of initial database articles and all new articles were noted and sourced.

All articles were then subjected to key inclusion criteria, these being: (1) the article specifically investigated the effect of dehydration on physical task performance; (2) the article was

* Corresponding author.
E-mail address: rorr@bond.edu.au (R.M. Orr)
Peer review under responsibility of Shanghai University of Sport.

http://dx.doi.org/10.1016/j.jshs.2014.09.004
2095-2546/

Table 1
Details of literature search: databases used, search terms, and filters.

Database	Filters	Number after exclusion	Number after inclusion	Total number	Duplicates	New articles
PubMed	2003–2013, human, English, clinical trial, RCT	4	3	3	0	3
CINHAL	2003–2013, human, English, research article, peer reviewed, RCT	1	1	1	1	0
Web of Science	Article, English, 2003–2013	72	8	8	5	6
SPORTSDiscus	Journal article, peer reviewed, English, 2003–2013	24	2	2	2	0
EBSCO: Academic Search Complete	Scholarly (peer reviewed) journals, 2003–2013, article, English	23	2	2	2	0

Abbreviation: RCT = randomized control trial.

published within the last 10 years; (3) the research involved human participants; (4) the article was published in English; and (5) the article was an original research article. For the purpose of this review, dehydration was defined as an increase in osmolality or similarly a decrease in body mass from a single exercise session/heat exposure. Physical tasks were defined as tasks that require physical exertion or activities that challenge the participant in a physical capacity.

The methodological quality of selected articles was assessed using the Downs and Black protocol.[9] The Downs and Black protocol employs a 27-question checklist to assess five key areas of methodological quality: statistical power, internal validity (bias and confounding), external validity, and reporting quality. The checklist comprised closed answer questions, where a "yes" is awarded 1 point and a "no" or "unable to determine" is awarded 0 point. There are two questions that have more points assigned to them. Question 5, reporting of confounding factors associated with the participants, is scored out of two (0 = no list, 1 = a partial list, 2 = a complete list of principle confounders). Question 27, a statistical power question, has scores derived from the number of participants involved in the clinical trial and is scored out of five. Scores were converted to a percentage of the total score by dividing each article's score by 32 (total possible score) and multiplying by 100. All studies were independently rated by the authors with the level of agreement measured using a Cohen's Kappa (κ) analysis of all raw scores (27 scores per paper). For final scores, any disagreements in points awarded were settled by consensus.

3. Results

From the initial search, 124 possible articles were identified from the database searches (Fig. 1). Of these articles, 108 were removed following review of the titles and abstracts against the five inclusion criteria. An additional seven articles were removed due to duplication. Six articles were added from the search of reference lists which identified previously unidentified articles. The remaining 15 articles were then reviewed in detail and considered against the inclusion criteria with nine papers retained for critical review.

The participants, methods, main findings and critical appraisal of the articles are shown in Table 2. The κ statistic for inter-tester agreement of the methodological quality of the studies indicated a "substantial" agreement (κ = 0.744).[10] The critical appraisal measures of power, quality of reporting, internal validity and external validity of the selected research articles were found to have reasonably high methodological scores (mean = 79% ± 4%) ranging from 72% to 81% using the Downs and Black checklist.[9] These scores are considered to represent a high standard of research.[11] Both the inability to blind the participants and the researchers, and poorly represented populations were identified as the main limitations of the studies identified for review.

The populations of the studies were all males, who were classified as healthy and active. Some of the participants were involved in specific sports including cycling,[8,12] rugby,[2] golf,[13] soccer,[14] and triathlon[7] with the remaining participants from the general population.[3,4,15] The average population size for the studies was nine participants ranging from seven to 12 participants. Seven of the nine studies[2,7,8,12–15] utilized a randomized crossover trial to allow for the capture of results from all participants across conditions whilst removing confounding effects in both learning and fatigue. The remaining two studies[3,4] used a one-day trial where the participants started in an euhydration state with exercise or heat exposure prescribed to achieve the dehydration condition for post-testing. There were a number of

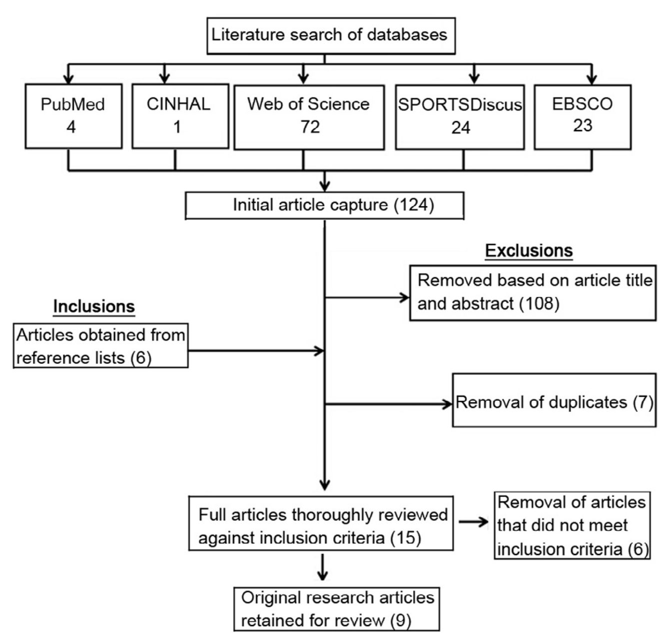

Fig. 1. A flow chart of the process used for the literature review.

different approaches employed by the studies to achieve a dehydrated state including: heat exposure,[2–4] fluid restriction,[2,7,8,12,13] and exercise.[7,12,14] There was one study that directly considered the effect of dehydration on aerobic performance,[2] whilst most looked at its effect on anaerobic performance.[3,4,7,8,12–15] Two of these anaerobic studies did however consider the effect dehydration had on the aerobic exercise that was undertaken to induce a dehydrated state.[8,12]

Two studies used sport specific skills to assess performance,[13,14] two the Wingate test,[3,15] and another two a graded exercise test to exhaustion.[7,12] One study looked at distance travelled in 30 min[2] while another used a 5-km time trial to determine performance impacts.[8] In the remaining study,[4] knee strength and standing vertical jump were used to determine the effect of dehydration on performance. Given these outcomes measure, the majority of the studies came to the conclusion that dehydration decreases performance[2–4,7,8,12–14] although one study found no difference between the euhydration and hypohydration trials.[15]

Four studies found that with dehydration there was an associated decrease in power output.[3,7,8,12] In addition, the captured studies noted increases in relative VO_2 and heart rate with dehydration,[2] decreased gross efficiency,[7] decreased speed,[8] decreased time to exhaustion,[12] and decreased sport-specific skills.[13] Two studies identified an increase in "Ratings of Perceived Exertion" levels with dehydration[2,14] with a third study noting a 70% increase in the severity of fatigue with dehydration.[3] In contrast, one study did find only a slight, non-significant increase in fatigue severity with dehydration.[15]

4. Discussion

Fluid loss due to PA is a daily occurrence for humans. Without replacement this fluid loss can lead to a state of dehydration. With the methodological scores of the evidence considered in this review found to be of good standard, the majority of research suggests that dehydration has a detrimental effect on physical performance, with the potential exception of activities lasting less than 15 s. This is unsurprising given evidence suggesting that a decrease in hydration of 3% has been shown to have an effect on the performance of further PAs.[3]

Upon investigating the impact of dehydration on aerobic performance most studies were found to only consider an aerobic exercise section as a segue between pre- and post-test. Aerobic exercise was used to help achieve the level of dehydration that the researches had set as their criteria.[4,7,8,12,14] However, some studies did utilize aerobic exercise as an outcome measure and not merely an intervention.[8,12] During these latter investigations the researchers found a decrease in aerobic performance with the participants that were in a hypohydrated or dehydrated state compared to baseline or euhydration state. Hillman et al.[8] discovered that with the reduced hydration in a warm climate (33.9 °C ± 0.9 °C *vs.* 23.0 °C ± 1.0 °C) the distance covered in their 90 min of cycling on a stationary ergometer significantly decreased ($p < 0.03$) when compared to a euhydrated state in the same participant.

Ebert et al.[12] found similar results. In their study, riders were allocated a low hydration restriction protocol of 50 mL per 15 min or a high hydration protocol of 300 mL per 15 min. The investigators note that during and following 120 min of submaximal riding there was a significant increase in the heart rates (low hydration: 187 ± 146 bpm; high hydration 183 ± 146 bpm; $p = 0.02$) and core body temperatures (low hydration: 39.5 °C ± 0.3 °C; high hydration: 39.1 °C ± 0.3 °C; $p < 0.001$) of the low hydration riders. Both the increased heart rate and increased body temperature are considered to be detrimental to performance.[12] There was one study that investigated just the aerobic performance on participants.[2] Aldridge et al.[2] explored the impact of dehydration on heart rate, perceived rating of exertion, and mean VO_2. They found significant differences in all three variables when comparing euhydration condition to the dehydration condition ($p \le 0.01$, $p \le 0.05$, $p \le 0.001$, respectively).

As opposed to aerobic exercise, the majority of studies investigated the effect of dehydration on anaerobic exercise.[3,4,7,8,12–15] Unlike the aerobic exercise studies, which had consistent findings, the studies investigating anaerobic exercise produced varying results. In the performance tests that lasted for longer periods of time (≥30 s) the investigators found that dehydration had a negative effect on performance.[3,4,7,8,12–14] However, for tests that lasted shorter than 15 s, including the standing vertical jump and 15 s Wingate anaerobic test there were no observed changes in performance.[4,15] A reason for these differences may relate to the energy system predominately used for each test. There are two main energy components that contribute to anaerobic performance, the alactic and anaerobic glycolytic (lactic) components.[16] These components work in conjunction with the aerobic energy system to meet the energy demand during exercise. Each energy system is active throughout exercise however one is usually more dominant than the others with the duration and intensity of the exercise influencing this.[16] For high intensity exercise that lasts up to 15–20 s the body predominately utilizes the alactic component;[16] this system does not require water.[17] For high intensity activity that lasts up to 2–3 min the body predominately uses the anaerobic glycolytic component;[16] a system that utilizes water to help in energy synthesis.[17] Water is used in the anaerobic glycolytic energy system to resynthesize pyruvate into glucose so that it can be recycled through the energy systems to create more energy, likewise the hydrogen ions stripped from the water produces energy when shuttled through the electron transport chain.[17,18] Water is utilized by the aerobic energy system to perform the same roles.[17] As such, a dehydrated state, where bodily water is limited, may reduce the ability of the anaerobic glycolytic and aerobic energy pathways to produce energy, and as such, have a negative impact on performance of tasks lasting 30 s or longer in duration.

The general findings from the reviewed research follow earlier studies prior to the review period. In regards to aerobic performance, previous research has typically found dehydration to negatively impact performance.[19–22] One study by Dengel et al.[23] did however fail to find changes in aerobic performance with hypohydration. It should be noted that participants in this study cycled at sub maximal intensities (50% VO_{2max}) for the duration. Similarly, findings investigating anaerobic

Table 2
Summary of the critical appraisal of included articles in this review.

Author	Participant	Variable	Intervention	Main finding	Critical appraisal score (%)
Aldridge et al.[2]	Eight regularly active male athletes – university rugby players	Independent: hydration status (EUH/HYPO) Dependent: aerobic exercise performance	Randomised crossover 1. 1 × 30 min cycle ergometer at 75 W	1. UOsm values for EUH and HYPO conditions were 385 ± 184 mOsm/kg and 815 ± 110 mOsm/kg, respectively 2. There was significant increases between EUH and HYPO conditions in mean VO_2 ($p \le 0.001$), HR ($p \le 0.01$), RPE ($p \le 0.05$) at the 30 min point of the test	81
Cheuvront et al.[15]	Eight healthy and physically active male subjects	Independent: hydration status (EUH/HYPO) Dependent: anaerobic exercise performance	Randomised crossover 1. 1 × 15 s Wingate (WAnT) 2. 3 h passive heat exposure 3. 3 × WAnT's at 0, 30, and 60 min's post heat exposure	1. HYPO condition had a significantly decreased body mass compared to EUH ($p < 0.001$) 2. No significant differences seen in relative peak power output between EUH and HYPO conditions (11.4 ± 1.0 and 11.7 ± 1.3 W/kg)	81
Ebert et al.[12]	Eight well-trained male cyclists	Independent: hydration status (HIGH CHO/LOW CHO) Dependent: cycling hill climbing performance	1 × maximal graded cycling test on a stationary ergometer to determine MAP Randomised crossover 1. 2 h ride on a stationary ergometer at 53% MAP 2. Hill climb time-to-exhaustion at 88% MAP, own their own bike on an 8% inclined treadmill	1. Significant difference between LOW CHO and HIGH CHO conditions in body mass loss (3.6 ± 0.6 and 1.3 ± 0.5 % body mass respectively, $p < 0.05$) 2. Significant difference in time to exhaustion on hill climb test between LOW CHO and HIGH CHO conditions ($p = 0.002$), with a 28.6% ± 13.8% decrease in times in the LOW group	72
Edwards et al.[14]	Eleven moderately active male soccer players (two players did not complete MR conditions)	Independent: (FI, NF, and MR) Dependent: soccer match play and fitness variables	Randomised crossover 1. 45 min pre-match cycle ergometer (90% VT) 2. Completion of a 45 min soccer match 3. Immediate post-match sport-specific and mental concentration tests	1. U_{SGM} significantly increased ($p < 0.05$) post-match compared to pre-match in the NF test, however no significant change in the FI and MR tests 2. A significant decrease in both NF and MR (13% and 15%, respectively) in distance covered in the post-match performance test when compared to the FI test	75
Hayes and Morse[4]	Twelve male university students	Independent: hydration status increasing levels of HYPO Dependent: strength, jump capacity, and neuromuscular function	1. Six resistance exercise bouts Heat exposure between each bout 2. Heat exposure of 20 min jogging in a warm environment chamber 3. Resistance exercise bouts consisted of a unilateral knee extension in isometric and isokinetic concentric conditions and a standing vertical jump	1. Subjects had a significant decrease in body mass, maximal isometric, and isokinetic strength during the study ($p < 0.001$, $p < 0.05$, $p < 0.05$, respectively) 2. However no significant change was seen in jump height, EMG, or maximal isokinetic strength at 120°/s	75
Hillman et al.[8]	Seven competitive male cyclists	Independent: hydration status (EUH and DE in W and T conditions) Dependent: 5 km cycling TT	Randomised crossover 1. 90 min cycling at 95% lactate threshold 2. 5 km TT	1. % DE significantly increased in the DE–W condition compared to pre-exercise ($p < 0.01$) 2. DE–W also had significant decreases in power output compared to all other conditions in both the 90 min cycle and 5 km TT ($p < 0.03$, $p < 0.02$)	81

(*continued on next page*)

Table 2 (*continued*)

Author	Participant	Variable	Intervention	Main finding	Critical appraisal score (%)
Jones et al.[3]	Seven healthy males	Independent: hydration status (EUH/HYPO) Dependent: UL and LL PO	1. 2 × UL and LL – 30 s Wingate tests 2. Heat exposure until dehydration of 3.0% body mass loss was achieved 3. 2 × UL and LL – 30 s Wingate tests	1. UL and LL mean PO were significantly decreased between EUH and HYPO (7.17%, $p = 0.016$; 19.20%, $p = 0.002$) 2. UL and LL peak PO were significantly decreased between EUH and HYPO (14.48%, $p = 0.013$; 18.36%, $p = 0.013$)	81
Smith et al.[13]	Seven athletic low-handicap experienced male golfers	Independent: hydration status (EUH/DE) Dependent: sport-specific and cognitive motor performance	Randomised crossover 1. Sport-specific performance test: hitting 30 golf balls in a laboratory-based netted, enclosed swing area 2. Cognitive ability test: distance judgment	1. Body mass in the DE condition was significantly reduced when compared to base line ($p < 0.01$) 2. Shot distance and off target accuracy were both significantly different between the EUH and DE conditions. (−14.1%, $p < 0.001$; 3.8%, $p = 0.001$) 3. There was also a significant decrease between EU and DE conditions in the cognitive tests ($p < 0.001$)	81
Van Schuylenbergh et al.[7]	Nine national level male triathletes	Independent: hydration status (EUH/DE) Dependent: HR, PO, RER	Randomised crossover 1. Graded cycling test to exhaustion 2. 2 h endurance exercise bout (including fluid replacement for the EUH condition) 3. Graded cycling test to exhaustion	1. DE post-exercise test was significantly shorter and had reduced PO than the other tests ($p < 0.05$) 2. Oxygen uptake was not significantly different and RER was significantly decreased in all post-exercise test conditions ($p < 0.05$)	81

Abbreviations: EUH = euhydration; HYPO/DE = hypohydration/dehydration; HIGH CHO = high carbohydrate; LOW CHO = low carbohydrate; HR = heart rate; RPE = rating of perceived exertion; MAP = maximal aerobic power; VT = ventilatory threshold; W = warm; T = thermoneutral; TT = time trial; PO = power output; UL = upper limb; LL = lower limb; RER = respiratory gas exchange ratio; MR = mouth rinse; FI = fluid intake; NF = no fluid; EMG = electromyography; VO_2 = oxygen consumption.

performance were mixed.[20] Where one study by Greiwe at al.[24] found no change in isometric strength or muscle endurance following a sauna induced state of hypohydration, a study by Torranin et al.[25] did find a decrease in muscle strength-endurance likewise following a sauna induced hypohydration state.

Given the findings of this review and consideration of earlier research, research suggests that athletes participating in exercise of greater than 30 s in duration would benefit from pre-hydrating to a state of euhydration prior to their event, and to continually ingest fluids to match those lost during exercise to maintain a state of euhydration. While coaches often broadly consider hydration status (potentially more often during games as opposed to training), they may not fully appreciate the impact a dehydrated state could have on performance or the potentially life threatening incidence that may arise from this physiological state. As such, through maintaining a state of euhydration, the athlete's level of fatigue may be decreased, as may their relative VO_2, heart rate, and rating of perceived exertion, the consequences of which will see an increased level of performance.

Urine specific gravity (USG) presents one means monitoring an athlete's level of hydration. Typically a quick and easy method, USG can be captured through various means including hydrometry, reagent strips, and refractometry with refractometry considered the more accurate.[26] USG scores from these measures can then be compared to ratings tables (like those provided by Casa et al.[27]) to measure an athlete's level of hydration. Apart from USG, there are some other methods for measuring hydration status including urine osmolality (laboratory measure) and pre- and post-body weight mass (field measure). Urine osmolality measures may be more timely and delayed[28,29] and are considered interchangeable with USG measures.[29] In the field, body mass measures can provide a guide as to fluid loss through sweat loss. As a general guide, a loss of more than 1%–2% of body mass indicates that the athlete did not ingest sufficient fluid during the event.[30] Conversely, if body mass loss was lower than this amount fluid intake may have been more than that was required for the event or activity.[30] It should be noted, however, that changes in body weight do not account for athletes that are dehydrated on their initial pre-activity measure. As such, the latter statement regarding limited body mass changes and sufficient hydration may be misleading.[30]

When considering the research presented and choice of hydration measures, the coach should consider the potential differences in athlete sweat rates. Research does suggest that sweat rates differ from person to person, through factors like fitness and percentage of body fat.[30,31] Furthermore, higher intensity exercise or higher ambient temperature and humidity may likewise influence sweat rates,[30] as may the nature of the activity being undertaken.[32]

When discussing the real world implications of these finding both the nature of the PA being conducted (duration and intensity) and the environments in which it is undertaken must be considered. In the majority of the studies reviewed the PA was cycling on either an ergometer or a personal bicycle on an incline treadmill. Considering this, only three studies had participants from a trained cyclist population. In one study[2] the researchers used cycling as the outcome measure on a population trained to play rugby. As such the outcome measure lacked sport specificity and could not be considered a true representation of the general population. Furthermore, in all but one study,[14] the research was completed in a laboratory setting and hence a controlled environment which may limit the true impacts of the PA on levels of hydration as they exclude environmental conditions (like breeze, surface temperature, *etc*.) which may further influence the hydration of the athlete.

Three key limitations identified for this review were 1) the small number of "current" research studies that met the inclusion criteria, 2) the differences between protocols for the studies, and 3) the differences in subjects and their training histories. With only nine studies meeting the inclusion criteria for critical review, drawing firm conclusions from their results was difficult especially given the variability in protocols and outcome measures. Secondly, the variance in outcome measures across the studies limited the drawing of dedicated recommendations. Thirdly, the subjects from each study varied completing different activities, factors known to influence sweat rates and hence potential hydration status.[32]

5. Conclusion

In conclusion, dehydration appears to have a negative impact on physical performances that are longer than 30 s in duration. Even though there is no significant negative impact on tasks lasting less than 15 s in duration, a state of euhydration is suggested to be maintained during all PA. It is also a suggestion of this review that further research be conducted into the impacts of dehydration on physical performance within the specific task environment while employing performance outcome measures that closely mimic the athlete's key physical tasks.

References

1. Buskirk ER, Iampietro PF, Bass DE. Work performance after dehydration: effects of physical conditioning and heat acclimatization. *J Appl Physiol* 1958;**12**:189–94.
2. Aldridge G, Baker JS, Davies B. Effects of hydration status on aerobic performance for a group of male university rugby players. *J Exerc Physiol Online* 2005;**8**:36–42.
3. Jones LC, Cleary MA, Lopez RM, Zuri RE, Lopez R. Active dehydration impairs upper and lower body anaerobic muscular power. *J Strength Cond Res* 2008;**22**:455–63.
4. Hayes LD, Morse CI. The effects of progressive dehydration on strength and power: is there a dose response? *Eur J Appl Physiol* 2010;**108**:701–7.
5. Ganio MS, Armstrong LE, Casa DJ, McDermott BP, Lee EC, Yamamoto LM, et al. Mild dehydration impairs cognitive performance and mood of men. *Br J Nutr* 2011;**106**:1535–43.
6. Coris EE, Ramirez AM, Van Durme DJ. Heat illness in athletes: the dangerous combination of heat, humidity and exercise. *Sports Med* 2004;**34**:9–16.
7. Van Schuylenbergh R, Vanden Eynde B, Hespel P. Effect of exercise-induced dehydration on lactate parameters during incremental exercise. *Int J Sports Med* 2005;**26**:854–8.
8. Hillman AR, Vince RV, Taylor L, McNaughton L, Mitchell N, Siegler J. Exercise-induced dehydration with and without environmental heat stress results in increased oxidative stress. *Appl Physiol Nutr Metab* 2011;**36**:698–706.
9. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *J Epidemiol Community Health* 1998;**52**:377–84.
10. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics* 1977;**33**:159–74.
11. Kennelly J. *Methodological approach to assessing the evidence. Reducing racial/ethnic disparities in reproductive and perinatal outcomes*. New York, NY: Springer; 2011.p.7–19.
12. Ebert TR, Martin DT, Bullock N, Mujika I, Quod MJ, Farthing LA, et al. Influence of hydration status on thermoregulation and cycling hill climbing. *Med Sci Sports Exerc* 2007;**39**:323–9.
13. Smith MF, Newell AJ, Baker MR. Effect of acute mild dehydration on cognitive-motor performance in golf. *J Strength Cond Res* 2012;**26**:3075–80.
14. Edwards AM, Mann ME, Marfell-Jones MJ, Rankin DM, Noakes TD, Shillington DP. Influence of moderate dehydration on soccer performance: physiological responses to 45 min of outdoor match-play and the immediate subsequent performance of sport-specific and mental concentration tests. *Br J Sports Med* 2007;**41**:385–91.
15. Cheuvront SN, Carter 3rd R, Haymes EM, Sawka MN. No effect of moderate hypohydration or hyperthermia on anaerobic exercise performance. *Med Sci Sports Exerc* 2006;**38**:1093–7.
16. Gastin PB. Energy system interaction and relative contribution during maximal exercise. *Sports Med* 2001;**31**:725–41.
17. Nelson D, Cox M. *Lehninger: principles of biochemistry*. 5th edition. New York, NY: WH Freeman and Company; 2008.
18. Wilmore JH, Costill DL, Kenney L. *Physiology of sport and exercise*. 4th edition. Champaign, IL: Human Kinetics; 2008.
19. Barr SI, Costill DL, Fink WJ. Fluid replacement during prolonged exercise: effects of water, saline, or no fluid. *Med Sci Sports Exerc* 1991;**23**:811–7.
20. Barr SI. Effects of dehydration on exercise performance. *Can J Appl Physiol* 1999;**24**:164–72.
21. González-Alonso J, Mora-Rodríguez R, Below PR, Coyle EF. Dehydration markedly impairs cardiovascular function in hyperthermic endurance athletes during exercise. *J Appl Physiol* 1997;**82**:1229–36.
22. McGregor SJ, Nicholas CW, Lakomy HK, Williams C. The influence of intermittent high-intensity shuttle running and fluid ingestion on the performance of a soccer skill. *J Sports Sci* 1999;**17**:895–903.
23. Dengel DR, Weyand PG, Black DM, Cureton KJ. Effect of varying levels of hypohydration on responses during submaximal cycling. *Med Sci Sports Exerc* 1992;**24**:1096–101.
24. Greiwe JS, Staffey KS, Melrose DR, Narve MD, Knowlton RG. Effects of dehydration on isometric muscular strength and endurance. *Med Sci Sports Exerc* 1998;**30**:284–8.
25. Torranin C, Smith DP, Byrd RJ. The effect of acute thermal dehydration and rapid rehydration on isometric and istonic endurance. *J Sports Med Phys Fit* 1979;**19**:1–9.
26. Stuempfle KJ, Drury DG. Comparison of 3 methods to assess urine specific gravity in collegiate wrestlers. *J Athl Train* 2003;**38**:315–9.
27. Casa DJ, Armstrong LE, Hillman SK, Montain SJ, Reiff RV, Rich BS, et al. National Athletic Trainers' Association position statement: fluid replacement for athletes. *J Athl Train* 2000;**35**:212–24.

28. Shirreffs SM, Maughan RJ. Urine osmolality and conductivity as indices of hydration status in athletes in the heat. *Med Sci Sports Exerc* 1998;**30**:1598–602.
29. Shirreffs SM. Markers of hydration status. *Eur J Clin Nutr* 2003;**57**:S6–9.
30. Maughan RJ, Shirreffs SM. Development of individual hydration strategies for athletes. *Int J Sport Nutr Exerc Metab* 2008;**18**:457–72.
31. Havenith G, van Middendorp H. The relative influence of physical fitness, acclimatization state, anthropometric measures and gender on individual reactions to heat stress. *Eur J Appl Physiol* 1990;**61**:419–27.
32. Godek SF, Bartolozzi AR, Godek JJ. Sweat rate and fluid turnover in American football players compared with runners in a hot and humid environment. *Br J Sports Med* 2005;**39**:205–11.