Chapter 1

General Introduction

1.1 Fluid requirements and replacement strategies within a military context

The Research and Technology Organisation (RTO) of the North Atlantic Treaty Organisation (NATO) states in the executive summary of their Human Factors and Medicine Panel Specialists’ meeting held in Boston 2003 that: “There is a need to provide more precise estimates of fluid requirements to lessen the loads that the soldier might have to carry and reduce costs associated with water transport and re-supply” (RTO-MP-HFM-086).

The extent to which humans need to replace their fluid losses during exercise remains contentious despite more than 60 years of focused research (Adolph 1947; Ladell 1947; Ladell 1955; Ladell 1965; Montain et al. 2001; Noakes 2003; Passe et al. 2007; Sawka and Noakes 2007; Sawka et al. 2007; Gonzalez et al. 2009). While it is now accepted that exercisers should not be encouraged to drink “as much as tolerable” there is still no consensus of the optimum rate of fluid ingestion during exercise.

The recently modified ACSM guidelines advise that exercisers should drink sufficiently to ensure that their body mass loss during exercise is less than 2% (Sawka et al. 2007). More recently the US Army Research Institute of Environmental Medicine (USARIEM) proposed sweat loss prediction equations ranging from ~575 g/hr to ~1092 g/hr (based on an individual with a body surface area of 1.9 m^2) for various workloads, environmental and clothing configurations in order to more accurately predict fluid replacement volumes during work and exercise (Gonzalez et al. 2009). Others (Noakes 2003; Noakes 2007) argue that drinking to the dictates of thirst is the biologically appropriate behaviour that optimises performance and is unrelated to heat illness regardless of the exact level of dehydration that develops during exercise.

This debate has special relevance for the military since soldiers ingesting fluid *ad libitum* will drink less that those who are forced to drink in order to lose less than 2 % of their body mass during exercise. Many soldiers drinking *ad libitum* according to the dictates of their thirst will drink less, develop “voluntary dehydration” and will therefore need to carry less water during military operations. In order to investigate these possibilities, there is a need for field studies to establish the optimum rates at which soldiers should ingest fluid during exercise.

1.2 Statement of the problem

Knowledge of a soldier’s water needs is vital in ensuring the health, safety and performance of military forces especially in hot arid conditions (Adolph, 1947) in which the provision of water is the critical factor determining ability to sustain military operations. Furthermore accurate knowledge of the fluid needs of military personnel provides much needed information to be applied within the logistics of the transport and provision of water to the front during military operations. The logistical burden of providing water during military operations is second in magnitude only to the supply of battery power to drive military equipment and systems.

Unfortunately providing an excess of water contributes to the burden of the payloads imposed on the dismounted foot soldier, whereas the provision of too little water could have detrimental health consequences. By determining the optimal water requirements of soldiers, one can ensure their safety and physiological comfort while optimising their payload burdens. The correct water replacement strategy will provide safe hydration levels without affecting soldier performance, while potentially reducing the payload burden imposed on the modern soldier.

1.3 Aims and objectives

The aim of the research was to determine the optimal rates of fluid ingestion by military personnel. In turn this could reduce the mass, in the form of water, soldiers might need to carry on military missions.

Accordingly we posed the following questions:

1. What are the rates of fluid ingestion freely chosen by soldiers during exercise?
2. Are these freely chosen (*ad libitum*) rates of fluid ingestion sufficient to protect against major fluid and electrolyte imbalances as evaluated by?
    - Total body water (TBW),
    - Serum sodium concentration [Na^+]; and
    - Plasma osmolality (POsm)
3. Are these freely chosen (*ad libitum*) rates of fluid ingestion sufficient to maintain safe thermoregulation during exercise?

4. Can changes in body mass be used as an accurate surrogate measure for changes in TBW during prolonged exercise?

1.4 Abstract

Herewith follows an abstract of the initial and subsequent chapters of the thesis. Where the applicable chapter consisted of a scientific manuscript the abstract of the manuscript is presented below. Note that the formats of these abstracts are as determined by the scientific journal to which the manuscript was submitted.

Chapter 1

Briefly describes fluid replacement within the military context as well as general introduction and structure of the thesis.

Chapter 2

Knowledge of a soldier's water needs is vital to ensure the health, safety and performance of military forces. Water also contributes to the burden of payloads imposed on the dismounted foot soldier. By determining the optimal water requirements of soldiers, it is possible to ensure safe hydration while decreasing payload burdens. The primary objective of this study was to evaluate the effect of *ad libitum* vs. restricted fluid replacement on selected hydration status markers and performance in three military tasks that evaluated handling, aiming and trigger control during shooting, observation skills and fine motor skills. The secondary objective was to determine if a restricted intake of 300 ml/hr could be considered a safe minimum recommended fluid intake. Data was collected during a field study involving 4 hours of exercise, simulating a

route march over 16 km. Fifty seven subjects participated in the study; the average age of the subjects was 29.5 ± 1.3 (SD) years. The mean pre-exercise body mass of the *ad libitum* group (N = 29) was 70.4 ± 13.3 kg compared to 69.3 ± 8.9 kg in the restricted group (N =28). The mean environmental dry bulb temperature during the study was 24.6°C with a range of 21.0°C to 28.2°C. The mean total fluid intake of the *ad libitum* group was 2.1 ± 0.9 litres compared to 1.2 ± 0.0 litres in the restricted group. There were no significant differences between or within groups for either urine specific gravity (USG) or urine osmolality (UOsm) before or after the exercise period. The *ad libitum* and restricted intake groups respectively lost a mean of 1.05 kg ± 0.77 (1.5%) ($p<0.05$) and 1.34 kg ± 0.37 (1.9%) ($p<0.05$) during the march. Predicted sweat rate was 608 ml/hr ± 93 compared to 762 ml/hr ± 162 in the *ad libitum* group ($p<0.05$). Apart from a non-significant ($p>0.05$) weak ($r^2=0.25$) and medium ($r^2=0.67$) correlation between the post-exercise USG and UOsm for the restricted intake and *ad libitum* groups respectively, there were no other significant medium or strong correlations between either USG or UOsm and any other variable, including total fluid intake and body mass loss during exercise.

Compared to their pre-exercise scores the restricted intake group produced better scores in their post exercise performance measures for all five variables of the three military tasks whereas the *ad libitum* group improved their scores in three of the variables with a decreased performance in two variables. Thus 300 ml/h intake of the restricted group could be considered a current safe minimum hourly water intake for soldiers of similar mass under conditions similar to those of the study (moderate, dry climate over mixed terrain for similar exercise durations) at similar exercise intensities.

Although variables including soldier functional performance and urinary markers of hydration were measured in this study, fluid balance as determined by changes in total body water (TBW) was not. The lack of correlation between urinary markers and hydration status posed questions regarding the accuracy and validity of these markers to assess fluid balance during exercise. This led to the investigation and application of the measure of TBW though the diluted isotope method in the subsequent studies. Additional measures to evaluate electrolyte balance (serum sodium concentration and plasma osmolality) and thermoregulation (peak exercise core temperature) was added to the methods of the subsequent studies.

Chapter 3

This chapter provide a concise literature summary of the measurement of TBW through the diluted isotope method. This serves as background information describing the technique and methods as applied during the studies presented in Chapters 4, 5 and 6. The introductions, results and discussions of all the subsequent chapters incorporate comprehensive literature on recommendations for fluid replacement during exercise and military training.

Chapter 4

Opportunities to determine optimal rates of fluid ingestion could reduce the mass soldiers might need to carry on military missions. The first objective was to evaluate the effects of an *ad libitum* fluid replacement strategy on total body water (TBW), core temperature, serum sodium concentrations [Na^+] and plasma osmolality (POsm). The second objective was to determine if an *ad libitum* water intake was sufficient to maintain these variables during exercise. A third objective was to determine whether changes in body mass are an accurate measure of changes in TBW. A field study was conducted with 15 soldiers performing a 16.4 km route march. The average age of the subjects was 27 ± 4.6 (SD) years. Their mean hourly *ad libitum* fluid intake was 383 ± 150 ml. Predicted sweat rate was 626 ± 122 ml/hr. Despite an average body mass loss of 1.0 kg ± 0.50 TBW, POsm and serum [Na^+] did not change significantly during exercise. There was a significant ($p<0.05$) linear relationship with a negative slope between post-exercise serum [Na^+] and changes in both body mass and % TBW. Post-exercise POsm and serum [Na^+] were significantly related ($p<0.05$). Higher post-exercise % TBW was associated with lower post-exercise POsm and serum [Na^+] levels. There was no relation between % body mass loss and peak exercise core temperature (38.1 ± 0.6°C). Conclusion: A mean *ad libitum* water intake of 383 ml/h, replacing approximately 61% of body mass losses during 4 hours of exercise maintained TBW, peak exercise core temperature, POsm and serum [Na^+] despite a 1.4% body mass loss. A reduction in body mass of 1.4% (1.0 kg) was not associated with a reduction in TBW.

Chapter 5

The extent to which humans need to replace fluid losses during exercise remains contentious despite years of focused research. The primary objective was to evaluate *ad libitum* drinking on hydration status to determine whether body mass loss can be used as an accurate surrogate for changes in total body water during exercise. Data was collected during a 14.6 km route march (WBGT of 14.1). 18 subjects with an average age of 26 ± 2.5 (SD) years participated. Their mean *ad libitum* total fluid intake was 2.1 ± 1.4 litres during the exercise. Predicted sweat rate was 1.289 ± 0.530 L/hr. There were no significant changes ($p>0.05$) in total body water, urine specific gravity or urine osmolality despite an average body mass loss ($p<0.05$) of 1.3 kg ± 0.45 during the march. Core temperature rose as a function of marching speed and was unrelated to the % change in body mass. This suggests that changes in mass do not accurately predict changes in total body water ($r = -0.16$) either because the body mass loss during exercise includes losses other than water or because there is an endogenous body water source that is released during exercise which does not require replacement during exercise, or both. *Ad libitum* water replacement between 65% and 70% of sweat losses maintained safe levels of hydration during the experiment. The finding that total body water was protected by *ad libitum* drinking despite ~2% body mass loss suggests that the concept of “voluntary dehydration” may require revision.

Chapter 6

The guidelines to establish safe environmental conditions for exercise are based in part on the concept of a thermal prescriptive zone in which humans exercising at an externally-regulated (fixed) work rate (exercise intensity) are unable to reach thermal equilibrium. This data suggest that it is dangerous for humans to exercise competitively at ambient temperatures in excess of 34°C, especially when the air humidity is increased. Yet there are isolated reports of unusual self-paced human athletic performances in extreme heat. As part of a series of experiments to determine the minimal fluid requirements of soldiers during route marches, we were granted the opportunity to study a group of 18 exceptionally well conditioned and heat-adapted members of the South African National Defence Force. The soldiers participated in an individually-timed, competitive 25 km route march while wearing full battle dress and carrying 26 kg in a dry bulb temperature that reached 44.3ºC. The average age of the subjects was 26 ± 3.7 (SD) years. Their mean hourly *ad libitum* water intake was 1264 ± 229 ml. Predicted sweat rate was 1789 ± 267 ml/hr. Despite an average body mass loss of 2.73 ± 0.98 kg, plasma osmolality and serum sodium concentrations did not change significantly during exercise. Total body water (TBW) fell 1.47 kg (2.0%) during exercise ($p<0.05$). However, the change in body mass did not accurately predict the changes in TBW as a 1:1 ratio. There was a significant ($p<0.05$) linear relationship with a negative slope between post-exercise serum [Na^+] and changes in both body mass and % TBW. Higher post-exercise % TBW was associated with lower post-exercise POsm and serum [Na^+] levels. There was no relation between % body mass loss and peak exercise core temperature (40.3 ± 0.9°C) or time taken to finish the march. Subjects maintained low core body temperatures in part by behaviour modifications which included resting in the shade. We conclude that these subjects maintained plasma osmolality, serum [Na^+] and safe core body temperatures by (i) adopting a pacing strategy which included intermittent rest in the shade; (ii) very high rates of *ad libitum* water intake and (iii) by allowing a small reduction in TBW to maintain serum [Na^+] despite probable sweat sodium losses of > 200 mmol. Our findings support the hypothesis that humans are the mammals with the greatest capacity for exercising in extreme heat, an adaptation that may have special significance for the evolution of the Homo sapiens.

Chapter 7

A manuscript by Baker et al. (2009) was published in the European Journal of Applied Physiology stating that changes in body mass accurately and reliably predicts changes in TBW and could therefore by used as an indication of hydration status during prolonged exercise.

Since the results of Baker and associates were in direct conflict with the results of the studies presented in this thesis document, a thorough review of their methods and results were performed. A letter was addressed to the editor of the European Journal of Applied Physiology in order to raise concerns over the results and the manner in which they were calculated.

Chapter 8

Chapter 8, provide a summary, conclusion of the interpretations on the findings, and indications for further research.

Summary

The extent to which humans need to replace their fluid losses during exercise remains contentious despite more than 60 years of focused research. Unfortunately, apart from the inherent physiological risk associated with “under” or “over” hydration, providing an excess of water contributes to the burden of the payloads imposed on the dismounted foot soldier. The correct water replacement strategy will provide safe hydration levels without affecting soldier performance, while potentially reducing the payload burden imposed on the modern soldier. This debate has special relevance for the military since soldiers ingesting fluid *ad libitum* will drink less that those who are forced to drink in order to lose less than 2 % of their body mass during exercise.

The main findings of this research effort are that the mean *ad libitum* fluid (water) intake of soldiers ranged from 383 ml/hr to 1264 ml/hr and that these *ad libitum* rates of fluid ingestion were sufficient to protect against major fluid, electrolyte and thermoregulatory imbalances. Furthermore the findings suggest that changes in body mass can not be used as an accurate surrogate measure for changes in TBW during prolonged exercise.

Current position stands on fluid replacement proposes that the mass loss during exercise should not exceed 2% of the starting body mass.

The findings of this research effort do not support this prescription and indicates that large changes in body mass did not cause deleterious physiological changes during exercise. The study raises questions about the validity of the term “voluntary dehydration” that was first coined more than 60 years ago. Indeed this study invites a more thorough interrogation of the use of the term “dehydration” which should be used only when there is a proven reduction in TBW and not, as this study shows, merely a reduction in body mass during exercise.

1.5 Publications and presentations

Nolte HW, Noakes TD, van Vuuren B. 2011. Trained humans can safely exercise in extreme dry heat when drinking water ad libitum. Submitted to the Journal of Sports Sciences.* Accepted for publication on 18 February 2011.

Nolte H, Noakes TD, van Vuuren B. 2010. Ad libitum Fluid Replacement in Military Personnel during a 4-Hour Route March. *Medicine and Science in Sports and Exercise*, 42(9): 1675-1680.

Nolte HW and Noakes TD. 2010. Comments on Baker et al.’s “Change in body mass accurately and reliably predicts change in body water after endurance exercise”. *European Journal of Applied Physiology*. Letter to the editor, 108(5): 1061-1064.

Nolte H, Noakes TD, van Vuuren B. 2010. Protection of total body water content and absence of hyperthermia despite 2% body mass loss ("voluntary dehydration") in soldiers drinking ad libitum during prolonged exercise in cool environmental conditions. *British Journal of Sports Medicine*. Accepted for Publication: 2 August 2010.

Noakes TD and **Nolte HW.** 2011. Reply on Baker's comments to Nolte and Noakes: "change in body mass accurately and reliably predicts change in body water after endurance exercise". European Journal of Applied Physiology. Letter to the editor, 111: 889-890. (Included as Appendix).

Tam N, **Nolte HW** and Noakes TD. 2011. Changes in Total Body Water Content During Running Races of 21.1 km and 56 km in Athletes Drinking Ad libitum. Clinical Journal of Sports Medicine, 21(3): 218-225. (Included as Appendix).

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1.6 References

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Passe, D., Horn, M., Stofan, J., Horswill, C. and Murray, R. 2007. Voluntary dehydration in athletes despite favourable conditions for fluid intake. *International Journal of Sport Nutrition and Exercise Metabolism* 17(3): 284-95.

RTO-MP-HFM-086. Maintaining Hydration: Issues, Guidelines, and Delivery. 2003. *RTO meeting proceedings*. RTO Human Factors and Medicine Panel (HFM) Specialists' Meeting held in Boston, United States.

Sawka, M.N., Noakes, T.D. 2007. Does dehydration impair exercise performance? *Medicine and Science in Sport and Exercise,* 39: 1209-17.

Sawka, M.N., Burke, L.M., Eichner, E.R., Maughan, R.J., Montain, S.J., and Stachenfeld, N.S. 2007. American College of Sports Medicine. Special Communications. Position Stand: Exercise and Fluid Replacement.

Chapter 2

Effect of *ad libitum* and restricted fluid replacement strategies during prolonged exercise on various hydration markers and performance of selected military tasks in soldiers

Article:

Nolte, H.W., Noakes, T.D. and van Vuuren, B. 2009. Effect of *ad libitum* and restricted fluid replacement strategies during prolonged exercise on various hydration markers and performance of selected military tasks in soldiers.

2.1 Introduction

Water is the largest single constituent of the human body and is essential for cellular homeostasis and life. Knowledge of a soldier's water needs is vital in ensuring the health, safety and performance of military forces especially in arid conditions (Adolph, 1947) in which the provision of water is the critical factor determining ability to sustain military operations.

Unfortunately providing an excess of water contributes to the burden of the payloads imposed on the dismounted foot soldier, whereas the provision of too little water could have detrimental health consequences. By determining the optimal water requirements of soldiers, one can ensure their safety and physiological comfort while optimising their payload burdens. The correct water replacement strategy will provide safe hydration levels without affecting soldier performance, while potentially reducing the payload burden imposed on the modern soldier.

Foot soldiers can not usually be expected to carry masses in excess of 50% of their own body mass. These masses have a negative impact on soldier endurance, situation awareness and the ability to respond quickly and accurately to threat. In arid environments water comprises a significant amount of this mass. For example, during deployment in Afghanistan, United States soldiers often carried water supplies for missions lasting between 1-3 days representing 9-10 kg or in excess of 30% of their fighting load (RTO-MP-HFM-086). However few studies have attempted to establish a safe minimum level of replacement for soldiers during operational activities. Such minimal values would reduce payload requirements while maintaining optimal fluid levels and contribute to overall system performance and mission success.

Thus the primary objective of the study was to evaluate the effect of *ad libitum* vs. restricted fluid replacement protocol (fluid intake limited to exactly 300 ml/hour) on selected hydration status markers and military performance measures in a group of 57 dismounted infantry soldiers during a simulated route march of 16km lasting 4 hours.

The secondary objective was to determine if the volume of 300 ml/h could be considered a safe minimum recommended fluid intake without negatively affecting either the hydration status or performance of this group of dismounted soldiers during the march.

Subject selection

Ethical clearance for this study was obtained from the Research Ethics Committee of the South African Military Health Services (SAMHS) of the SANDF. A request for subjects was put forward to the SANDF in order to identify soldiers that were experienced and conditioned to route marches with payloads of up to 35 kg. All the subjects were medically fit to participate in the study and none was suffering from any musculoskeletal injuries. All subjects had recently passed the Chief of the Army Fitness Test. Subjects were told that they could terminate their participation at any stage without any consequences to their careers. Subjects were required to voluntarily sign an informed consent form before they participated in the study. The subjects were asked to provide basic demographic information for record purposes. Anthropometric measurements were included to predict fat and muscle percentage distributions using the Drinkwater and Ross method (Ross and Marfell-Jones, 1991). Two days prior to the field study the subjects performed a multi staged shuttle run test (Lèger and Lambert, 1982) to determine predicted maximal oxygen consumption (VO_2max). A qualified exercise scientist facilitated a warm-up and stretching session with the subjects prior to the performance of the test.

2.2 Materials and methods

Performance Measures

On the day of the study performance was recorded during selected military tasks in order to compare the results prior to and upon completion of the 4 hour exercise intervention. Shooting skills were evaluated on an Electronic Learning Aiming Correction System (ELACS) shooting simulator. All of the subjects were familiar with the use of this simulator. The simulator graded the subjects on three variables of their shooting skills namely handling, aiming and trigger control during the task.

An observation task required the subjects to observe, spot and identify military related objects that were positioned in the operational area. They needed to identify various objects and report back their location regarding position and distance from where they were standing using standard military protocol. These objects were rotated or replaced with alternatives for the post-exercise observation task. The objects were placed to evaluate near, far and peripheral vision of the soldiers. A plastic weapon magazine and dummy metal rounds were used in a task which evaluated fine motor skills. The subjects had to unload and reload a magazine in the fastest possible time. The time was measured from the moment the soldier picked up the loaded magazine until he had completed the unloading and reloading and placed the magazine back on the table.

Exercise intervention

Subjects wore standard issue combat dress with military boots, battle jacket and bush hat. The battle jackets of each of the subjects were similarly packed with mass to the amount of 20 kg. One member of each group carried a Global Positioning System (GPS) and radio to ensure communication and tracking of the groups in terms of speed and direction. The route was 4.0 km and was repeated four times for a total march distance of 16 km which took 4 hours to complete. Subjects were randomly assigned to either the restricted (300 ml/h) or *ad libitum* intake group. Subjects in the *ad libitum* group were instructed to drink as desired while the restricted group were instructed to finish 300 ml but no more within each hour of the four hour intervention. Neither of the two groups was allowed to eat during the study. The ambient temperature, wind speed, relative humidity, solar radiation and barometric pressure were recorded for the duration of the study.

Hydration markers

Select measures to identify acute changes in hydration status were measured including body mass, urine specific gravity (USG) and urine osmolality (UOsm). Sweat rates were predicted from body mass changes as well as fluid intake and urine output during the exercise period. Sweat rates were estimate as follows:

Sweat rate = ((pre body mass – post body mass) + (fluid intake – urine produced))/exercise time

Sweat rates so calculated are not corrected for respiratory water loss as well as CO_2 loss and O_2 gain. Nude body mass was recorded prior and upon completion of the route march with an electronic scale (accurate to the nearest 100 grams). Subjects were provided with towels to dry excess perspiration prior to weighing. Subjects were required to empty their bladders prior to each weighing; these voids were used for USG and UOsm analyses prior to and upon completion of the route march.

Statistical analyses

In order to determine which statistical test would be most suited for the comparisons of the *ad libitum* and restricted intake groups, the differences (paired differences) between the group results were calculated. The distributions (in the form of histograms) of paired differences of all the results were plotted with the number of classes as calculated according to the Rule of Sturge. The normality of this distribution was tested by means of the Shapiro-Wilks' W test. The statistical Rule of Sturge states that the number of classes equals N x 1.4 + 1 (Where: N = sample size). T-tests were used to compare *ad libitum* and restricted intake results where the distribution of the paired differences was normal. Where the distribution of the paired differences was not normal, the non-parametric alternative to the T-test, the

Wilcoxon Rank Sum Test was used to compare *ad libitum* and restricted intake results. A Pearson's product moment correlation coefficient was used to determine relationships between appropriate variables. Statistical significant differences between the *ad libitum* and restricted intake results were indicated by a p-value of less than 0.05. The statistical analyses were completed using the STATISTICA© software package (Statsoft, 2000).

2.3 Results

Fifty seven subjects that met the selection criteria volunteered for the study. Table 1 presents the military experience; body mass, stature, predicted VO_2max as well as predicted percentage body fat and muscle for the two groups. There were no statistically significant differences between any of these variables for the two groups. Results for the ambient temperature, wind speed, relative humidity, solar radiation and barometric pressure for the duration of the study are presented in Table 2.

Table 1: Subject information for both groups

		Minimum	Mean (±SD)	Maximum
Ad Libitum **Group (N = 29)**	**Years military service**	6.0	8.1 (1.0)	10.0
	Body mass (kg)	50.4	70.6 (13.4)	103.2
	Stature (mm)	1594	1724 (81)	1895
	Predicted VO_2 max (ml/kg/min)	24.9	36.7 (6.8)	50.2
	Body fat (%)	6.3	12.1 (4.2)	20.8
	Muscle (%)	36.7	44.6 (3.7)	50.1
Restricted Group (N = 28)	**Years military service**	6.0	8.2 (1.1)	11.0
	Body mass (kg)	55.2	69.3 (8.8)	88.4
	Stature (mm)	1600	1723 (71)	1895
	Predicted VO_2 max (ml/kg/min)	26.8	37.3 (4.4)	46.8
	Body fat (%)	5.9	11.5 (3.9)	22.9
	Muscle (%)	38.7	44.2 (2.5)	48.1

Table 2: Prevailing environmental conditions during the study

	Minimum	Mean (±SD)	Maximum
Dry bulb temperature [°C]	21.0	24.6	28.2
Solar radiation [W/sq.m]	257.0	599.2	781.0
Barometric pressure [mbar]	640.0	641.0	644.2
Wind speed [km/h]	1.1	1.9	2.7
Relative humidity [%]	16.0	20.7	47.0

Table 3 presents the mean hourly water intake of the *ad libitum* group; the restricted group drank 300 ml/hr. Considering the mean total fluid intake during the 4 hour exercise period the *ad libitum* group consumed 2.1 litres compared to the 1.2 litres of the restricted group, a difference of 224 ml/hr during the 4 hours or a total of 900ml. Table 4 presents the results for pre- and post-exercise values and changes in mean USG for both groups. There were no significant differences between or within groups for USG before or after the exercise period. Table 5 presents the results for pre- and post-exercise values and changes in UOsm for both groups. There were no significant differences between or within groups for UOsm before or after the exercise.

Table 3: Mean fluid intake of *ad libitum* group

	Minimum	**Mean (±SD)**	**Maximum**
Water intake (ml/hr)	228	524 (227)	1000

Table 4: USG results for both groups pre- and post-exercise

		Minimum	**Mean (±SD)**	**Maximum**
Restricted Group (N = 28)	**USG (pre-exercise)**	1.010	1.020 (0.00)	1.025
	USG (post-exercise)	1.015	1.021 (0.00)	1.025
	% Change		0.11	
***Ad Libitum* Group (N = 29)**	**USG (pre-exercise)**	1.010	1.019 (0.00)	1.030
	USG (post-exercise)	1.005	1.019 (0.00)	1.025
	% Change		-0.07	

Table 5: UOsm results for both groups pre- and post-exercise

		Minimum	**Mean (±SD)**	**Maximum**
Restricted Group (N = 28)	**UOsm (pre-exercise) [mmol/kg]**	356	893.2 (170)	1183
	UOsm (post-exercise) [mmol/kg]	599	878.5 (130)	1141
	% Change		-1.65	
***Ad Libitum* Group (N = 29)**	**UOsm (pre-exercise) [mmol/kg]**	429	868.2 (193)	1242
	UOsm (post-exercise) [mmol/kg]	84	805.6 (290)	1173
	% Change		-7.2	

Table 6 presents the body mass changes and calculated sweat rates of both the *ad libitum* and restricted intake groups. The differences in the sweat rates between the groups were statistically significant while the decrease in body mass were significant for both groups but not different between groups. Figures 1 and 2 respectively present the relationship between the total volume consumed and the post exercise UOsm and USG for the *ad libitum* intake group. Figures 3 and 4 respectively present the relationship between the change in body mass and UOsm and USG for the *ad libitum* group. Figures 5 and 6 respectively present the relationship between the change in body mass and UOsm and USG for the restricted intake group.

Table 6: Body mass loss and sweat rate prediction results for both groups pre- and post-exercise (* = p<0.05)

		Minimum	**Mean (±SD)**	**Maximum**
Restricted Group (N = 28)	**Mass (pre-exercise) [kg]**	54.20	69.33 (8.9)	88.00
	Mass (post-exercise) [kg]	53.70	67.99 (8.7)	86.40
	Body mass loss [kg]	0.50	1.34* (0.37)	1.60
	Body mass loss [%]	0.9	1.9	2.60
	Sweat Rate [ml/hr]	395	608* (93)	0.755
***Ad Libitum* Group (N = 29)**	**Mass (pre-exercise) [kg]**	50.40	70.41 (13.3)	102.00
	Mass (post-exercise) [kg]	49.30	69.36 (13.0)	99.90
	Body mass loss [kg]	0.50	1.05* (0.77)	2.10
	Body mass loss [%]	0.9	1.5	2.0
	Sweat Rate [ml/hr]	0.489	762* (162)	1.189

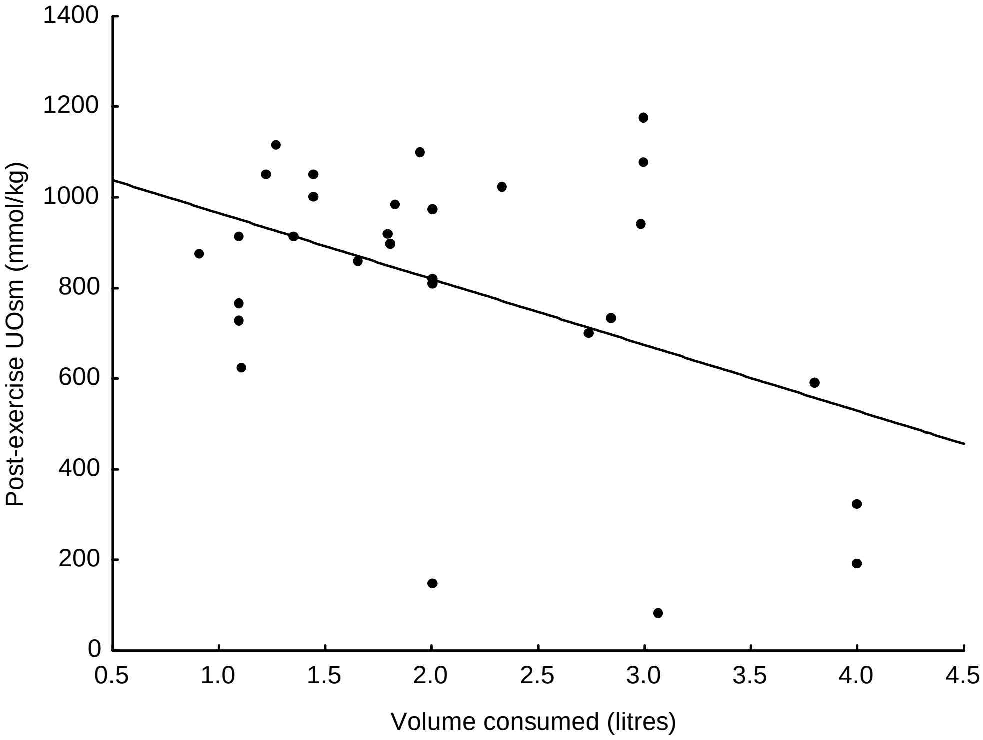

Figure 1: The relationship between total water intake and urine osmolality for the *ad libitum* intake group (N =29) (r = -0.45, p>0.05)

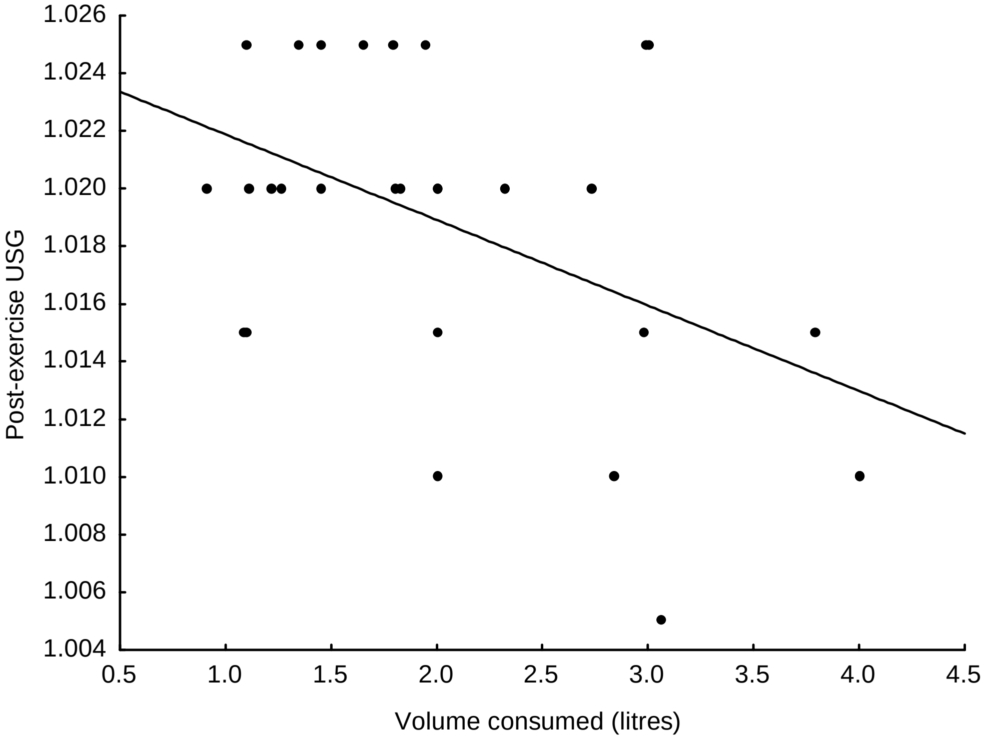

Figure 2: The relationship between total water intake and urine specific gravity for the *ad libitum* intake group (N =29) (r = -0.48, p>0.05)

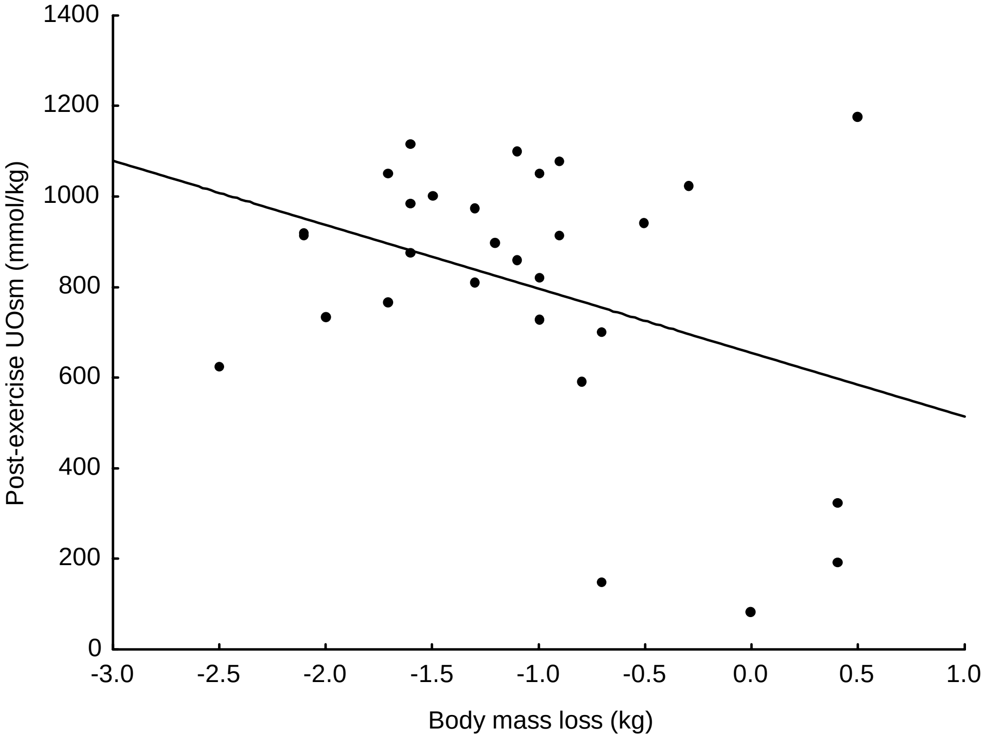

Figure 3: The relationship between body mass loss and urine osmolality for the *ad libitum* intake group (N =29) (r = -0.37, p>0.05)

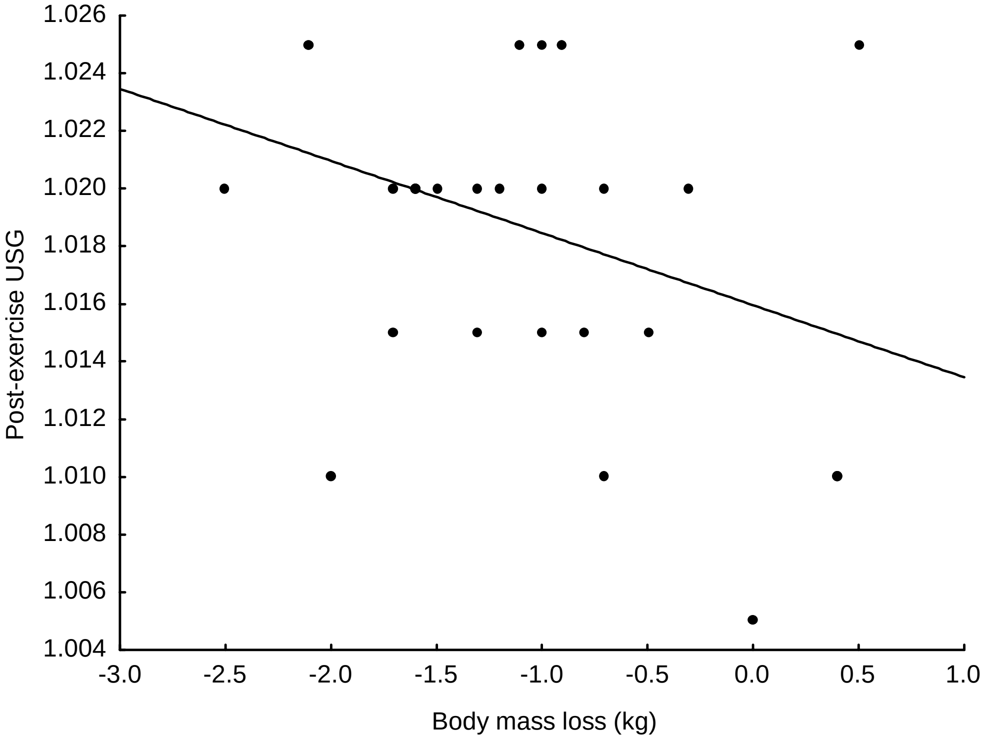

Figure 4: The relationship between body mass loss and urine specific gravity for the *ad libitum* intake group (N =29) (r = -0.34, p>0.05)

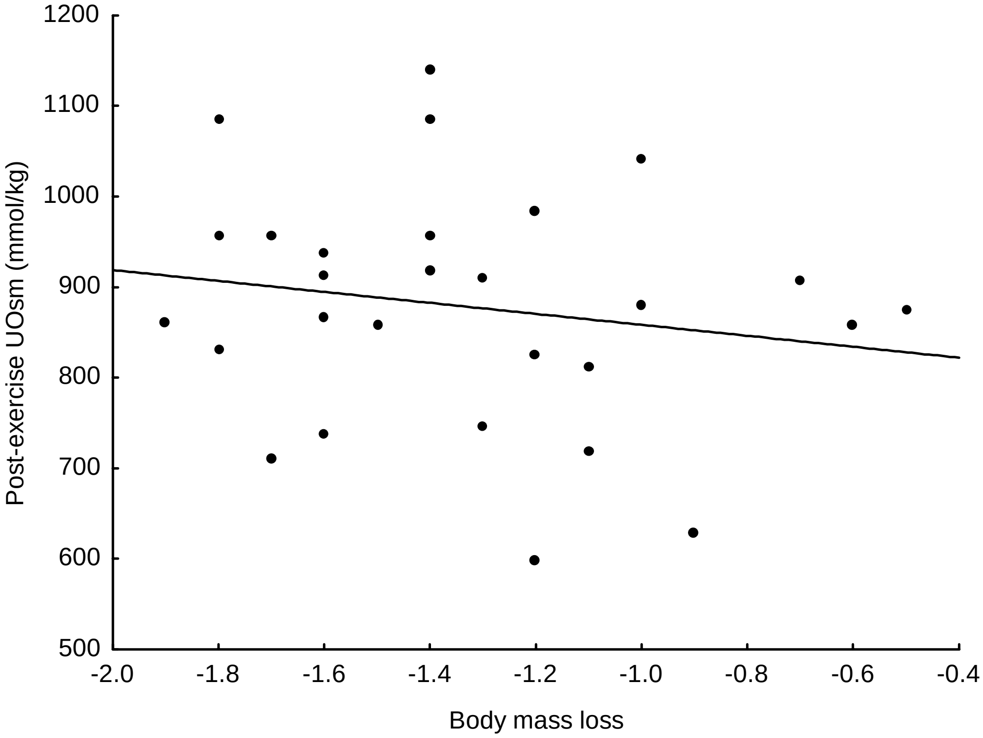

Figure 5: The relationship between body mass loss and urine osmolality for the restricted intake group (N =29) (r = -0.17, p>0.05)

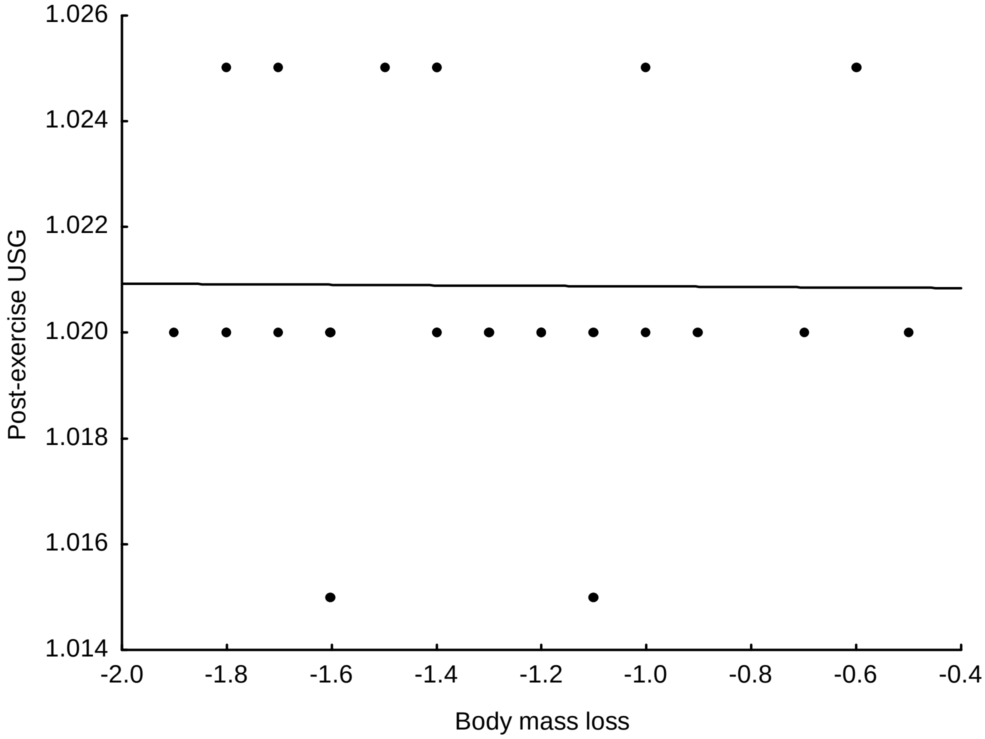

Figure 6: The relationship between body mass loss and urine specific gravity for the restricted intake group (N =29) (r = -0.07, p>0.05)

Table 7 presents the mean handling performance scores for the shooting simulator task before and after the march. Although not statistically significant, the restricted group performed better than the *ad libitum* group after the exercise and presented with a larger within group improvement. Table 8 presents the mean aiming performance scores for the shooting simulator task pre- and post-exercise. Table 9 presents the mean trigger control performance scores for the shooting simulator task pre- and post-exercise. The *ad libitum* group showed statistically significantly better scores during the pre route march task despite the random assignment of each group. The restricted group improved their performance significantly after the route march while the *ad libitum* group showed a non-significant decrease in their performance of this task.

Table 10 presents the observation performance scores for both groups pre- and post-exercise. There may well be contributing factors in the improvement in performance such as changes in light contrast due to time of day testing. However performance did not deteriorate despite the exercise intervention and different fluid replacement strategies and the completion of a 4 hour route march. Table 11 presents the fine motor skill scores for both groups pre- and post-exercise. Although not statistically significant, the *ad libitum* group performed better than the restricted intake group after the exercise and presented with a larger within group improvement.

Table 7: Shooting simulator handling results for both groups

		Minimum	Mean (±SD)	Maximum
Restricted Group (N = 28)	**Handling results (pre-exercise)**	15.00	60.70 (24.2)	88.00
	Handling results (post-exercise)	15.00	68.04 (19.9)	89.00
	% Change		12.08	
***Ad Libitum* Group (N = 29)**	**Handling results (pre-exercise)**	16.00	66.48 (26.0)	90.00
	Handling results (post-exercise)	16.00	67.26 (19.8)	90.00
	% Change		4.18	

Table 8: Shooting simulator aiming results for both groups

		Minimum	Mean (±SD)	Maximum
Restricted Group (N = 28)	**Aiming results (pre-exercise)**	7.00	30.37 (17.0)	69.00
	Aiming results (post-exercise)	5.00	33.22 (14.4)	63.00
	% Change		9.39	
***Ad Libitum* Group (N = 29)**	**Aiming results (pre-exercise)**	7.00	35.78 (17.3)	67.00
	Aiming results (post-exercise)	6.00	35.48 (15.4)	64.00
	% Change		-0.83	

Table 9: Shooting simulator trigger control time results for both groups

(* = $p<0.05$)

		Minimum	Mean (±SD)	Maximum
Restricted Group (N =28)	**Trigger control time score (pre-exercise)**	8.00	41.33* (28.1)	86.00
	Trigger control time score (post-exercise)	15.00	54.08 (23.1)	83.00
	% Change		30.84	
***Ad Libitum* Group (N = 29)**	**Trigger control time score (pre-exercise)**	17.00	62.48* (24.2)	86.00
	Trigger control time score (post-exercise)	8.00	60.63 (22.6)	86.00
	% Change		-2.96	

Table 10: Observation skill results for both groups (* = p<0.05)

		Minimum	Mean (±SD)	Maximum
Restricted Group (N = 28)	**Number of objects identified out of possible 8 (pre-exercise)**	3	5.96 (1.6)	8
	Number of objects identified out of possible 8 (post-exercise)	4	7.04 (1.1)	8
	% Change		17.96*	
***Ad Libitum* Group (N = 29)**	**Number of objects identified out of possible 8 (pre-exercise)**	1	6.21 (1.5)	8
	Number of objects identified out of possible 8 (post-exercise)	4	7.07 (1.1)	8
	% Change		13.89*	

Table 11: Fine motor skills results for both groups

		Minimum	Mean (±SD)	Maximum
Restricted Group (N = 28)	**Time (pre-exercise)**	01:03	01:23 (00:19)	02:44
	Time (post-exercise)	00:57	01:18 (00:12)	01:38
	% Change		-4.19% (improvement)	
***Ad Libitum* Group (N = 29)**	**Time (pre-exercise)**	00:58	01:20 (00:19)	02:16
	Time (post-exercise)	00:52	01:15 (00:15)	01:53
	% Change		-7% (improvement)	

2.4 Discussion

Our first relevant finding of this study was that despite a significant ($p<0.05$) body mass loss presented by the restricted intake group during exercise (1.9% of pre-exercise body mass) the only significant difference between the two groups was the predicted sweat rate during exercise. The sweat rate was significantly higher in the ad libitum group at 762 ml/hr vs. 608 ml/hr ($p<0.01$).

The differences in sweat rates might be attributed to the differences in the water volumes consumed during the march since the *ad libitum* group ingested on average 900 ml more water during the four hour route march. Other than this difference, there were no significant differences between the two groups for any of the post-exercise hydration variables that were measured despite differences in body mass loss and total fluid intake.

Our second relevant finding was the lack of any significant correlations between the urinary indices and hydration status (Figures 1 to 6). Apart from a non-significant, weak ($r^2=0.25$) and medium strong ($r^2=0.67$) correlation between the post-exercise USG and the post-exercise UOsm for the restricted intake and *ad libitum* groups respectively, there were no other significant medium or strong correlation between either USG or UOsm and any other variable, including total fluid intake and body mass loss (Figures 3 to 6) during the exercise period. The duration in the renal response to exercise induced dehydration will result in significant delays in urinary electrolyte changes so that these measures are of little value to assess fluid balance status. Laursen et al. (2006) also reported that changes in body mass were unrelated to core temperature, serum sodium concentration and urine specific gravity in athletes completing a 226 km Ironman Triathlon. The lack of an apparent correlation between these urinary markers and body mass loss and fluid intake should caution against the use of these markers when accurate hydration status assessments are required.

Both USG and UOsm are often used to monitor hydration status in field settings due to the non-invasive and cost effective nature of these methods. According to Armstrong et al. (1994) and Armstrong (2005) USG and UOsm will both increase with dehydration and are strongly correlated. Previously Armstrong et al. (1994) presented correlation values of 0.96 (r^2). However, others argue that urine osmolality is not a good indicator of changes in total body water (TBW) (Hackney et al., 1995, Ruby et al., 2003 and Kavouras, 2002). For a “normally” hydrated (euhydrated) person, USG values range from 1.010 to 1.030. It has generally been accepted that a USG of less or equal to 1.020 represents euhydration and a USG greater than 1.030 represents dehydration (Popowski et al., 2001). Normal urine osmolality should be between 300 – 900 mmol/kg.

In the setting of such variability, there may be no single threshold at which the urine osmolality accurately predicted the hydration status. In addition, urine osmolality is increased when osmotically active solutes are excreted, such as glucose, in patients with uncontrolled diabetes mellitus. For these reasons of high variability; dependence on solute excretion and lack of correlation with TBW changes, UOsm is not considered a good indicator of hydration status (Institute of Medicine of the National Academies, 2004). Further limitations regarding UOsm may include accuracy issues when used immediately after exercise and large inter-cultural differences as evident by mean differences between Germans (860 mmol/kg) and Poles (392 mmol/kg) (Armstrong, 2005 and Manz and Wentz, 2003).

None of the subjects in any of the groups presented with USG values in excess of 1.030 considered indicative of dehydration (Popowski et al., 2001).

Results of an intra-group comparison indicates that the restricted intake group presented with better scores in their post-exercise performance measures for all five variables while the *ad libitum* group presented with better scores for three ($p > 0.05$) of the variables and a decrease performance in two. The within group increase of 31% for the trigger control measure and 18% for the observational task of the restricted intake group were both statistically significant ($p < 0.05$). Furthermore the restricted intake group presented with better between group performance scores post-exercise in four of the possible five variables. However none of these differences were statistically significant.

The improvements present in the current study may be attributed to a warm-up effect on coordination as described by Adam et al. (2008), but it must be noted that performance did not deteriorate for the restricted intake group. But these results also suggest that aerobic exercise improves some aspects of military task performance since performance in the shooting, observational and fine motor tasks improved after the exercise bout.

Comparison of these results with other published studies is difficult since these tests form part of a custom designed soldier task measurement tool. Recently Adam et al. (2008) showed that moderate hypohydration of 3% did not effect cognitive or psychomotor performance in cold or temperate environments. Serwah and Marino (2006) investigated the combined effects of hydration and exercise heat stress on choice reaction time. They found that different levels of dehydration produced by different drinking regimes during up to 90 minutes of exercise in warm, humid conditions did not compromise choice reaction time. Similarly Szinnai et al. (2005) showed that dehydration of up to 2.6% body mass did not alter cognitive-motor function in healthy young subjects.

In surprising contrast Baker et al. (2007) found that vigilance-related attention of male basketball players was impaired by dehydration levels ranging between 1-4% concluding that fluid replacement is essential to prevent a decline in vigilance that occurs with dehydration in highly technically demanding sports. Were this finding universally true, we would have expected that performance in one or more of the tests that we performed should have been impaired.

Conclusion

The aim of this study was to compare the effects of an *ad libitum* and a restricted fluid replacement strategy on selected hydration markers and soldier performance in selected military tasks. We were unable to detect any superiority of the *ad libitum* drinking regime (525 ml/hr) compared to the restricted regime. Thus we conclude that a fluid ingestion rate of 300 ml/hr could be regarded as a safe minimum rate of fluid ingestion for male soldiers exercising under conditions similar to those in this study namely moderate, dry climate for similar exercise durations at equivalent exercise intensity. However, drinking *ad libitum* is probably the more appropriate response even though there was no measurable benefit associated with this slightly higher rate of fluid intake. Finally we show that urinary measures are poorly related to hydration status and recommend that the diluted isotope technique be applied during future research in order to accurately assess changes in total body water during exercise. This technique would be able to relate body mass change to actual body water changes and could provide significant insight into the efficacy of *ad libitum* fluid replacement strategies in maintaining safe fluid levels during exercise.

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