Fluid Ingestion Attenuates the Decline in VO2peak Associated with Cardiovascular Drift

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Running Head: Fluid ingestion, cardiovascular drift and $\dot{V}O_{2peak}$

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ABSTRACT

Introduction/Purpose: This study investigated whether manipulation of cardiovascular drift (CV drift) by changing exercise duration or by fluid ingestion is associated with altered peak oxygen uptake ($\dot{V}O_{2peak}$). **Methods:** $\dot{V}O_{2peak}$ was measured in 11 trained men immediately after they cycled at 60% control $\dot{V}O_{2max}$ in 30°C, 40% relative humidity for 15, 60 and 120 min with no fluid (15NF, 60NF, 120NF) or 120 min with fluid (120F). Stroke volume (SV), heart rate (HR) and related measures were measured in 120NF and 120F at 15, 60, and 120 min. **Results:** Body mass decreased 0.7%, 2.3%, and 3.7% in 120F, 60NF and 120NF. SV at the end of submaximal exercise and $\dot{V}O_{2peak}$ measured immediately thereafter were reduced significantly ($P < .05$) from 15-min values in 120NF (13.8% and 8.7%), but not in 60NF (4.6% and 1.2%) or 120F (2.1% and 1.9%). **Conclusions:** The progressive decline in SV during prolonged, constant-rate submaximal exercise in a warm environment, reflective of increased cardiovascular strain associated with hyperthermia, dehydration and other changes that occur over time, reduces $\dot{V}O_{2peak}$. Fluid ingestion improves performance in prolonged exercise, in part, by mitigating the decline in SV and its determinants, and preserving $\dot{V}O_{2peak}$.

Key Words: Dehydration, Heart Rate, Heat, Maximal Oxygen Uptake, Stroke Volume

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Paragraph Number 1 Cardiovascular drift (CV drift), the progressive rise in heart rate (HR) and fall in stroke volume (SV) during prolonged, constant-rate exercise, has been described since the early 1960's (6,25). Although the exact cause is uncertain (3), the degree of CV drift that occurs in thermoneutral (13,22) and hot conditions (11,20) is directly related to the degree of dehydration and associated hyperthermia. In prolonged exercise (2 h) when dehydration is completely prevented by fluid ingestion, the increase in HR is attenuated and decrease in SV is eliminated in thermoneutral (13) and in hot conditions (11,19).

Paragraph Number 2 Although there has been extensive research on the factors affecting and mechanisms underlying CV drift, its implications for physical performance are uncertain. It is not known if the progressive fall in SV over time is benign and can be overcome if exercise intensity is increased, or if it reflects altered circulatory capacity and is associated with a reduced peak oxygen uptake ($\dot{V}O_{2peak}$) and performance capability. A number of studies (5,25,26) have reported that prolonged exercise has a modest detrimental effect on $\dot{V}O_{2peak}$, but these studies did not measure $\dot{V}O_{2peak}$ at the same points in time as the variables characterizing CV drift and did not establish a link between the two measures. We (30) recently observed that a 12% increase in HR and a 16% decrease in SV that occurred between 15 and 45 min of submaximal cycling in the heat was associated with a large reduction in $\dot{V}O_{2peak}$ (19%) and time (35%) on a graded exercise test administered immediately after submaximal exercise. Although an attempt was made to manipulate CV drift with fluid ingestion in that study, the treatment was not effective because the exercise duration was too short. Therefore, it is not known if the association in that study reflected cause and effect.

Paragraph Number 3 The current study was designed to provide experimental data to determine whether or not manipulation of CV drift is associated with corresponding changes in $\dot{V}O_{2peak}$ and performance. CV drift was manipulated in two ways. First, the association between CV drift and $\dot{V}O_{2peak}$ was studied following two different durations of exercise in which different degrees of CV drift occurred. This was accomplished by measuring CV drift between min 15 and

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min 60, and between min 15 and min 120 of cycling and assessing the changes in $\dot{V}O_{2peak}$ that occurred between the same time points. Second, the magnitude of CV drift was manipulated with fluid ingestion. This was accomplished by performing a second 120-min trial, during which fluid was ingested to replace sweat losses, and measuring $\dot{V}O_{2peak}$ immediately after the 120 min. We hypothesized that 1) the reduced SV characterizing CV drift and an associated decrease in $\dot{V}O_{2peak}$ would be greater after 120 min than 60 min of cycling and 2) fluid ingestion would reduce the decrease in SV characterizing CV drift and the associated decrease in $\dot{V}O_{2peak}$.

METHODS

Subjects

Paragraph Number 4. Eleven male, healthy cyclists were recruited to participate in this study. They had been cycling training for 6 ± 3 yr and averaged 178 ± 97 km·wk^{-1} of cycling for the 6 mo prior to the study. Because subjects were training outdoors in hot weather during the summer months in which subjects were tested, they were naturally heat acclimatized. Their mean $\pm$ SD age, height, mass, and % body fat estimated from skinfolds were 26 ± 5 yr, 179.2 ± 5.6 cm, 75.63 ± 10.49 kg, and 13.5 ± 4.8 %, respectively. A sample size of 11 subjects is sufficient to detect a 5% decrease in $\dot{V}O_{2peak}$ using a two-tailed t-test for dependent samples at alpha $= 0.05$ and statistical power of 0.8, assuming individuals have a mean $\dot{V}O_{2max}$ of 55 ml·kg^{-1}·min^{-1} with a SD of 7 ml·kg^{-1}·min^{-1} and that the test-retest correlation for $\dot{V}O_{2max}$ is 0.95 (16). This study was approved by the Institutional Review Board, and subjects gave written informed consent prior to testing.

Research Design

Paragraph Number 5 A repeated-measures experimental design was used in which subjects were tested under all conditions. Following a control $\dot{V}O_{2max}$ test and 60-min practice ride, subjects completed four experimental trials, presented in a randomized order, separated by 7.4 ± 3.2 days. During each trial, the subject cycled at a power output eliciting 60% $\dot{V}O_{2max}$ (169 $\pm$ 16 W) under the following conditions: 1) 15 min without fluid ingestion (15NF), 2) 60 min

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without fluid ingestion (60NF), 3) 120 min without fluid ingestion (120NF), and 4) 120 min during which fluid was ingested (120F). Immediately following each ride, subjects completed a graded exercise test (GXT) to measure $\dot{V}O_{2peak}$.

   Paragraph Number 6 During 120F, equal volumes of a commercially available 7% carbohydrate-electrolyte (CE) sport drink at 30°C were ingested at min 15 and at 15-min intervals thereafter until min 105. The volume of fluid ingested was that estimated to be enough to prevent dehydration, based on the sweat loss measured during the practice ride plus that estimated to occur during the subsequent $\dot{V}O_{2peak}$ test.

   Paragraph Number 7 Metabolic, cardiovascular and thermal measures were obtained just prior to min 15, 60 and 120 in 120NF and 120F. Changes in cardiovascular measures between 15 min and the end of exercise were used to characterize CV drift. The $\dot{V}O_{2peak}$ measured in 15NF was used as the reference for changes over time in 60NF, 120NF and 120F, because fluid ingestion did not begin until after 15 min in 120F and conditions in 15NF were identical to the first 15 min of 120F. The control GXT and experimental trials were all conducted at the same time of day for a given subject in an environmental chamber at 30°C, 40% relative humidity (RH) and a wind speed of ~2.5 m·s^{-1}.

Protocol and Procedures

   Paragraph Number 8 Experimental controls. For the six days prior to each test session, subjects were instructed to maintain training volume and not to exercise vigorously the day before testing. For the three days prior to each test session, subjects were instructed to consume a similar diet. Compliance to training and diet instructions was monitored by training logs and diet records. For each test, subjects reported to the laboratory following a 3-h fast, but they were asked to remain hydrated by drinking 500 ml of water 1 h before arrival. They were instructed not to consume alcohol, caffeine, or non-prescription drugs the day before and the day of testing. On the day of the test, subjects completed a 24-h history questionnaire designed to determine adherence to pretest instructions. Urine specific gravity (USG) and tympanic body temperature

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(T_t) were measured. Subjects were not tested if they were dehydrated (USG > 1.030), if they had a fever (T_t > 37.8°C) or if they were not feeling well.

      Paragraph Number 9 Preliminary test session. During the preliminary test session, skinfold thickness at seven sites was measured with Lange calipers and body mass was measured to the nearest 10 g using an electronic scale (A&D Co., Ltd., Tokyo, model FW-150KA1). Following a warm-up of approximately 10 min at a self-selected power output, a control GXT to measure $\dot{V}O_{2max}$ was conducted. The test protocol consisted of cycling on an electronically-braked ergometer (Lode Excalibur Sport, Lode B.V., Groningen, NL) with the power output starting at 200 W and progressively increasing 25 W every 2 min until subjects could no longer continue. $\dot{V}O_2$ and related gas exchange measures were obtained by open-circuit spirometry using a PARVO Medics TrueOne 2400 Metabolic Measurement System (Parvo Medics, Inc., Salt Lake City, UT). HR and rating of perceived exertion (RPE) were measured at rest, every 2 min, and at the end of the $\dot{V}O_{2max}$ test. HR was measured with a Polar® Vantage XL heart rate monitor (Polar Electro, Inc. Woodbury, NY, model 145900). RPE was measured by the Borg 15-point category scale using standardized instructions (2). Three min after completion of the test, a finger-stick blood sample was obtained for determination of blood lactate concentration. Attainment of a $\dot{V}O_{2max}$ plateau was determined as described previously (30) by having subjects complete a follow-up bout of exercise 20 min after the GXT. Using this protocol, all subjects demonstrated a plateau in $\dot{V}O_{2peak}$, either during the graded test (4 occurrences) or during the subsequent bout (7 occurrences).

      Paragraph Number 10 Approximately 45 min after the test, subjects measured nude body mass and then completed a practice ride consisting of cycling for 1 h on a cycle ergometer. $\dot{V}O_2$ was measured for the first 10 min and the power output was adjusted to elicit 60% $\dot{V}O_{2max}$. The CO_2-rebreathing procedure for measuring $\dot{Q}$ was practiced at 15 and 60 min. Finally, nude body mass was remeasured for determination of sweat rate.

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 Paragraph Number 11 Experimental trials. Prior to each experimental trial, subjects measured nude body mass and inserted a rectal temperature probe. Next, a Teflon® venous catheter was inserted into an antecubital vein and kept patent with 0.5 ml of 10 USP units·ml^{-1} heparin lock flush. In order for plasma volume to stabilize, subjects then sat upright on the cycle ergometer for 20 min while skin temperature and laser Doppler flow probes were attached, resting HR was measured, and a blood sample was drawn. Subjects then cycled at 60% $\dot{V}O_{2max}$ for 15, 60, or 120 min. Rectal (T_{re}) and skin temperatures, and HR were measured continuously during each experimental trial. During the 2-h rides (120NF and 120F) metabolic, circulatory and perceptual measures were taken between min 7 and 15, min 52 and 60 and min 112 and 120. RPE was obtained, skin blood flow (SkBF) was measured, blood samples were drawn, expired air was analyzed for 2 min for measurement of $\dot{V}O_2$ and $\dot{V}CO_2$ using the Parvo Medics system, and two trials of CO_2-rebreathing were performed for measurement of $\dot{Q}$, in that order. To reduce random variability, HR at min 15, 60, and 120 was determined by using a regression equation formed from the 5-s data from min 10 to the end of submaximal exercise (15, 60, or 120 min) for each trial.

 Paragraph Number 12 At the end of cycling at 60% $\dot{V}O_{2max}$ for 15, 60 or 120 min, subjects immediately began a GXT with no cessation of cycling. Power output was initially increased 25 W above that maintained during the submaximal exercise (60% $\dot{V}O_{2max}$), with an additional 25 W increase in work rate every 2 min thereafter until subjects fatigued. $\dot{V}O_2$ and related metabolic measures were measured continuously over 30-s intervals throughout the test, HR was measured continuously, and RPE was measured every 2 min and at the end of the test. Three min following the test, a blood sample was taken and nude body mass was re-measured. The measurement of $\dot{V}O_{2peak}$ during the GXT was considered valid if 1) $\dot{V}O_2$ reached a plateau according to the criteria used for the control test (6 in 15NF, 2 in 60NF, 4 in 120 NF, and 6 in 120F), 2) $\dot{V}O_{2peak}$ reached the same value as in the control test (3 in 15NF, 5 in 60NF, 2 in 120

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NF, and 2 in 120F) or 3) the highest HR was within 5 bpm of the control maximum HR (2 in 15NF, 4 in 60NF, 5 in 120 NF, and 3 in 120F).

Paragraph Number 13 $\dot{Q}$ was measured using the indirect-Fick CO_2-rebreathing method, as described by Jones (15), using the Parvo Medics metabolic system and software. This involved measuring the $\dot{V}CO_2$, end-tidal CO_2 concentration, and the equilibrium CO_2 concentration following rebreathing in succession. Two rebreathing trials, separated by approximately one min, were always performed and averaged. The reliability of values from two trials in our laboratory is high (intraclass correlation = 0.93) (30). SV was calculated by dividing $\dot{Q}$ by HR. SkBF was measured with laser Doppler flowmetry (ALF 21D, Transonic Systems, Ithaca, NY) with a probe placed on the right forearm on the dorsal side. To reduce movement artifact during the measurement, subjects relaxed their wrist with the hand turned up on the ergometer handle bars while 20 s of data were recorded and averaged. Data were expressed as percentage of the 15-min value. The between-day test-retest reliability for SkBF during cycling at 60% $\dot{V}O_{2max}$ on two days was high (intraclass correlation = 0.83).

Paragraph Number 14 Rectal temperature (T_{re}) was measured by having the subject insert a temperature probe (Ellab, Inc., Arvada, CO, model MOV-55044-A) 10 cm past the anal sphincter. Skin temperature was measured with probes (Ellab, Inc., Arvada, CO, model MHF-18058-A) attached on the right lateral sub-deltoid, chest, thigh, and lateral calf as described by Ramanathan (24). The rectal and skin temperature probes were connected to a temperature data acquisition system (Ellab, Inc., model TM9608 with Eval 2.1 software), which collects and stores temperatures continuously. Mean skin temperature ($\overline{T}_{sk}$) was calculated according to the formula of Ramanathan (24).

Paragraph Number 15 During the 2-h rides, 2-ml blood samples were drawn into tubes containing EDTA. Blood lactate and glucose concentration were measured using a YSI 2300 Stat Plus Analyzer (Yellow Springs Instruments, Inc., Yellow Springs, OH). Plasma volume change (%ΔPV) during cycling relative to pre-exercise rest was estimated from measures of hemoglobin

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and hematocrit using the Dill-Costill equation (4). Hematocrit was measured in triplicate via the microhematocrit method. Hemoglobin was measured in duplicate using a HemoCue B-Hemoglobin photometer (HemoCue, Inc., Lake Forest, CA).

Statistical analysis

Paragraph Number 16 Statistical analyses were performed using SPSS v.11 for Windows (SPSS, Inc., Chicago, IL). Data are reported as means ± SD in the tables and as means ± SEM in the figures. To determine the effects of exercise duration on measures from data collected during 15NF, 60NF and 120NF, a one-way repeated-measures analysis of variance (ANOVA) was used to test the significance of mean differences. To examine the effects of fluid ingestion on data collected during 15NF, 120NF and 120F, a two-way (Condition × Time) repeated-measures ANOVA was used to test the significance of mean differences. Greenhouse-Geisser corrections were made when the assumption of sphericity was violated. Follow-up repeated-measures t-tests and the Bonferroni alpha correction were used when appropriate. An alpha level of 0.05 was used for all significance tests.

RESULTS

Hydration Status and Body Mass Changes

Paragraph Number 17 Hydration status at the beginning of 15NF, 60NF, 120NF, and 120F was similar, as indicated by pre-exercise body masses (75.4 ± 10.5, 75.1 ± 10.81, 75.2 ± 10.4, and 75.4 ± 10.9 kg) and USG (1.010 ± 0.006, 1.010 ± 0.006, 1.011 ± 0.005, and 1.010 ± 0.006) that were not significantly different among conditions.

Paragraph Number 18 Decreases in body mass resulting from sweat, blood, and respiratory water losses were greater in 60NF (2.3 ± 0.4%, $P < 0.001$) and 120 NF (3.7 ± 0.6%, $P < 0.001$) than following 15NF (1.3 ± 0.3%). Ingestion of an average of 2.35 ± 0.28 L of fluid in 120F prevented a significant change in body mass. Body mass decrease in 120F (0.5 ± 0.4 kg, 0.7 ± 0.5%) was significantly less than in 120NF ($P < 0.001$).

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Paragraph Number 19 Responses to submaximal exercise (Table 1). Between 15 and 60 min of 120NF, only a modest degree of CV drift occurred. SV did not change significantly (-6 ml, 4.6%, P = 0.128), HR increased 8 bpm (6.0%, P < 0.001), and $\dot{Q}$ did not change significantly. In the second hour of exercise, there was an additional decrease in SV of 9.2% and increase in HR of 7.8%. Thus, after 2 h with no fluid ingestion, substantial CV drift had occurred. SV was reduced 16 ml (13.8%, P < 0.001), HR was increased 19 bpm (13.8%, P < 0.001), and $\dot{Q}$ was unchanged compared to 15-min values.

Paragraph Number 20 SV did not significantly change over time in 120F (3 ± 10 ml), but decreased over 2 h in 120NF (16 ± 5 ml, P < 0.001). SV differences between 120NF and 120F developed in the second hour of exercise, as evidenced by a difference in SV at 2 h (P < 0.001) but not at 1 h. The increase in HR from 15 to 120 min (P < 0.001) was significantly less with fluid ingestion (10 ± 5 bpm) than without (19 ± 7 bpm) (P = 0.002). $\dot{Q}$ did not change significantly over time regardless of condition.

Paragraph Number 21 Plasma volume decreased ~6% from rest during the first 15 min, but did not change significantly between 15 and 60 min. A decline of 1.5 percentage points occurred during the second hour of exercise in 120NF (P = 0.003). In 120F, PV did not decrease after the initial 15 min as it did in 120NF (P = 0.008). In 120 NF, SkBF did not change significantly over time (P = 0.355, Fig. 1). In contrast, in 120F, SkBF did not change from 15 min to 60 min (P = 0.103), but was significantly higher than the 15-min value after 120 min (P = 0.045). T_{re} increased progressively by 1.1°C (P < 0.001) from min 15 to min 120 during the NF trials. The increase in T_{re} was less in 120F, and resulted in the 120-min value being significantly lower in 120F than in 120NF by 0.3°C (P = 0.005). $\overline{T}_{sk}$ decreased over time in both conditions (P = 0.016), but the change did not differ between conditions. RPE increased progressively during NF and F trials (P < 0.001), but was not different between conditions (P = 0.777).

Paragraph Number 22 Responses to peak exercise (Table 2). $\dot{V}O_{2peak}$ after 15 min (15NF) was not different from control. Compared to 15NF, the change in $\dot{V}O_{2peak}$ after 1 h

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(-1.2%) was not significant, but after 2 h with NF, $\dot{V}O_{2peak}$ was reduced significantly by 8.7% (P = 0.016) (Fig. 2). Peak HR, %ΔPV, and RPE did not differ between NF conditions, but peak ventilation ($\dot{V}_E$), respiratory exchange ratio (RER), and blood lactate were all lower at $\dot{V}O_{2peak}$ in 120NF compared to 15NF (P = 0.025, 0.026, and < 0.001, respectively) and 60NF (P = 0.035, 0.036, 0.020, respectively). Peak O_2 pulse was lower in 120NF compared to 15NF (P = 0.019). Peak T_{re} was higher in 60NF and 120NF compared to 15NF (P < 0.001 and P < 0.001). Peak T_{re} also was higher by 0.3°C in 120NF compared to 60NF (P < 0.001). The duration of the GXT to determine $\dot{V}O_{2peak}$ was shorter in 60NF (P = 0.002) and 120NF (P < 0.001) compared to 15NF, and shorter in 120NF compared to 60NF (P = 0.007). Likewise, peak power output (PO_{peak}) was lower in 60NF (P < 0.001) and 120NF (P < 0.001) compared to 15NF, and lower in 120NF compared to 60NF (P = 0.037) (Fig. 2).

Paragraph Number 23 A significant Condition × Time interaction (P = 0.035) in the two-way ANOVA indicated that the change in $\dot{V}O_{2peak}$ (Δ$\dot{V}O_{2peak}$) from 15NF to 120F was significantly less than the Δ$\dot{V}O_{2peak}$ from 15NF to 120NF (-1.3 and -5.1 ml·kg^{-1}·min^{-1}, respectively) (Fig. 3). $\dot{V}O_{2peak}$ in 120NF was significantly less than in 15NF (P = 0.005) and 120F (P = 0.035), but $\dot{V}O_{2peak}$ in 120F was not different from that in 15NF. Peak RER, RPE, %ΔPV, SkBF (Fig. 1) and HR did not differ between no fluid and fluid conditions, but these values were reached at lower peak $\dot{V}_E$ (P = 0.045) and blood lactate (P = 0.003) in 120NF than in 120F. A shorter GXT (P = 0.001) in 120NF than in 120F resulted in a lower PO_{peak} (P = 0.001, Fig. 2). Fluid ingestion (120F) resulted in a lower peak T_{re} (P = 0.002), but higher peak $\overline{T}_{sk}$ (P = 0.023). T_{re} was increased (P = 0.033) and SkBF was decreased (P = 0.005, Fig. 2) at $\dot{V}O_{2peak}$ compared to the 120-min time point in both conditions.

Paragraph Number 24 $\dot{V}O_2$, HR, and O_2 pulse and T_{re} during the GXTs as peak responses were approached are shown in Fig. 3. Only data from the first three stages of the test, which were completed by all subjects were statistically analyzed. $\dot{V}O_2$ values during the first three stages were higher in 60NF, 120NF and 120F than in 15NF by approximately 0.25 L·min^{-1} (P = 0.006-

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0.039). Differences in HR and T_{re} present at the end of submaximal exercise were maintained during the GXT up to the peak responses, with 120 NF > 60NF = 120F > 15NF throughout the test. There were no statistically significant differences among conditions ($P > 0.05$) in O_2 pulse for the first three stages of the GXTs.

DISCUSSION

Paragraph Number 25 The novel aspect of this study was measurement of $\dot{V}O_{2peak}$ and performance (time on GXT and PO_{peak}) immediately following 15 min of exercise (before CV drift began) and immediately following submaximal exercise in which different degrees of CV drift had occurred. The objective was to determine whether there is causal link between CV drift and a decrease in $\dot{V}O_{2peak}$ and performance as suggested in our previous research (30). The hypothesized link between CV drift and the reduction in $\dot{V}O_{2peak}$ and performance is based on previous research in which a decrease in SV during prolonged, constant-rate submaximal exercise persisted during subsequent maximal exercise, and was not compensated for by increased arteriovenous oxygen difference [(a-v)O_2 diff] difference or heart rate (5,25). In those studies, however, $\dot{V}O_{2peak}$ was not measured at the same points in time as measures used to characterize CV drift and CV drift was not manipulated to establish a causal link. Thus, even though SV was not measured during peak exercise on the GXTs, it is plausible to hypothesize that changes in $\dot{V}O_{2peak}$ in the present study would reflect persistent changes in SV associated with CV drift during the prior submaximal exercise.

Paragraph Number 26 The primary finding of this study was that manipulation of CV drift, by altering exercise duration and fluid ingestion, is associated with corresponding changes in $\dot{V}O_{2peak}$. $\dot{V}O_{2peak}$ was not reduced following 1 h of cycling in a warm environment when there was no significant reduction in SV. In contrast, following 2 h of exercise without fluid ingestion in which SV had decreased 14%, $\dot{V}O_{2peak}$ was reduced by 9%. Preventing dehydration with fluid ingestion during 2 h of cycling eliminated the decreases in SV and $\dot{V}O_{2peak}$. These experimental data show that the progressive reduction in SV during prolonged exercise in a warm

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environment, reflective of increased cardiovascular strain associated with hyperthermia, dehydration and other changes that occur over time, reduces $\dot{V}O_{2peak}$. Fluid ingestion improves performance in prolonged exercise, in part, by mitigating the decline in SV and its determinants, and preserving $\dot{V}O_{2peak}$.

Paragraph Number 27 We used a protocol similar to that of previous studies (11,13,20) involving 2 h of moderate-intensity exercise in a warm environment in which CV drift has been shown to occur progressively over time. By studying responses during and immediately following 1 and 2 h of cycling at ~60% $\dot{V}O_{2max}$ without fluid ingestion, we were able to determine the effects of two degrees of CV drift on $\dot{V}O_{2peak}$. After 1 h of exercise, HR had increased 6% above and SV had decreased 5% below 15-min values. Despite these changes, there was no significant difference between SV at min 15 and min 60. In the second hour of the 2-h exercise bout, HR increased an additional 8% and SV decreased an additional 9%. This resulted in a total CV drift of 14% in HR and SV, and significant differences in HR and SV from min 15. The development of CV drift in this fashion was expected under these ambient conditions (13). Other changes influencing CV drift, such as increased T_{re} and dehydration, also were similar to those observed in other studies (11,13,20).

Paragraph Number 28 In order to determine whether or not the different magnitude of CV drift was associated with a corresponding change in $\dot{V}O_{2peak}$, subjects performed a GXT immediately after submaximal exercise. After 60 min, when there was no significant decline in SV, there was no significant decline in $\dot{V}O_{2peak}$. However after 2 h, when SV had declined significantly (14%), $\dot{V}O_{2peak}$ also was reduced significantly (9%). The magnitude of reduction in $\dot{V}O_{2peak}$ after 2 h is similar to that observed in other studies in which $\dot{V}O_{2peak}$ was measured following prolonged exercise performed in similar ambient conditions (1,5). However, in these studies, $\dot{V}O_{2peak}$ was not measured at the same time points as the variables characterizing CV drift. Therefore, whether the change in $\dot{V}O_{2peak}$ reflected an effect of CV drift is unknown. The decrease in $\dot{V}O_{2peak}$ was less than that reported in our previous study (30) in which we observed a

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14% reduction in SV associated with a 19% reduction in $\dot{V}O_{2peak}$ between 15 and 45 min of cycling at 60% $\dot{V}O_{2max}$ in 35°C, 40% RH and no wind. The greater reduction in $\dot{V}O_{2peak}$ in that study was apparently the result of the greater degree of heat stress and CV drift.

Paragraph Number 29 In order to provide additional insight into whether the association between the decreases in SV and $\dot{V}O_{2peak}$ was causal, we used fluid ingestion to prevent dehydration and reduce CV drift over the 2-h time period. After 2 h, fluid ingestion decreased HR by 7% and increased SV by 12%, compared to 120NF. SV was maintained at the 15-min value, eliminating the decrease in SV observed in 120NF. Fluid ingestion also resulted in lower T_{re} after 2 h and eliminated the decrease in PV. The SV decrease and HR increase in the second hour of exercise were attenuated with fluid ingestion to the same degree as observed in other studies in which body weight change was prevented (11,20). The reduction in CV drift with the fluid ingestion was paralleled by a corresponding reduction in the magnitude of decrease in $\dot{V}O_{2peak}$ (from 9% to 2%). These findings support the hypothesis that attenuation of the decrease in SV with fluid ingestion attenuates the decline in $\dot{V}O_{2peak}$.

Paragraph Number 30 The reduction in $\dot{V}O_{2peak}$ in 120NF was not due to lack of effort or failure to achieve $\dot{V}O_{2peak}$. On the GXTs for this condition, the number of subjects who met each of the criteria for attaining $\dot{V}O_{2peak}$ was not systematically different from the other conditions. There were no statistically significant differences among trials in maximum RPE or maximum HR, and the mean values of 19 and ~190 bpm, respectively, indicate that a maximal effort was given. Similar peak HR in 120NF and in the other conditions strongly suggests cardiovascular capacity was reached in 120NF. Peak $\dot{V}_E$, RER and blood lactate were lower in 120NF than in 15NF, probably because a lower PO_{peak} was achieved and not because of a lack of degree of effort (1). Lower blood lactate at $\dot{V}O_{2peak}$ in 120NF, in which $\dot{V}O_{2peak}$ was reduced, also provides evidence that hydrogen-ion accumulation was not a factor inhibiting the ability to reach a power output eliciting $\dot{V}O_{2peak}$.

Paragraph Number 31 Because there was no difference in maximum HR among

conditions, and if peak (a-v)O_2 diff is not different under the conditions imposed in this study as would be expected (10,21), or increased during 120NF due to hemoconcentration, then, according to the Fick equation, the reduction in $\dot{V}O_{2peak}$ in 120NF would be due to a decrease in SV. If SV does not change or increases in proportion to the value present at the end of submaximal exercise with increasing $\dot{V}O_2$ during the GXT (8), the SV measured at the end of each submaximal exercise bout in this study would be representative of the SV at $\dot{V}O_{2peak}$. This interpretation is supported by the O_2 pulse data during the GXT. Similar values for O_2 pulse and $\dot{V}O_2$ during submaximal stages of the GXT for 60NF, 120NF and 120F, but reduced O_2 pulse at $\dot{V}O_{2peak}$ during 120NF suggest that reduced SV and $\dot{Q}$ during the submaximal stages of the test were compensated for by increased HR and (a-v)O_2 diff. However, when maximal HR and (a-v)O_2 diff were reached, the reduced SV and $\dot{Q}$ during 120NF likely caused reduced $\dot{V}O_{2peak}$. This interpretation is consistent with studies (5,25) that have shown that the reduction in SV that occurs during prolonged submaximal exercise persists when a maximal work rate is performed following the submaximal exercise.

Paragraph Number 32 It has been repeatedly shown that dehydration and the associated hyperthermia contribute to the progressive decrease in SV during prolonged submaximal exercise under conditions similar to those in the present study (9,11,12,20). These effects are apparent in our study. Plasma volume decreased and T_{re} increased progressively over time during 120NF, during which considerable reduction in SV occurred. Similar to findings in other studies (11,13,20), fluid ingestion during 120F that prevented dehydration eliminated the decrease in plasma volume between 15 and 120 min of exercise, and blunted the rise in T_{re} during the second hour of exercise, preventing a fall in SV. Dehydration and hyperthermia also may reduce $\dot{V}O_{2peak}$ (1,10,23), so it was not surprising to observe reduced $\dot{V}O_{2peak}$ in 120NF, during which greater dehydration and hyperthermia occurred than in the other conditions. The link between changes in $\dot{V}O_{2peak}$ and changes in SV associated with CV drift was apparently caused in large part by the effects of dehydration and hyperthermia that develop over time during prolonged exercise in a

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warm environment. This deduction is reinforced by the fact that the changes in CV drift and $\dot{V}O_{2peak}$ in 120F were similar to those in 60NF, when the changes in plasma volume and T_{re} were not different, indicating that the link between CV drift and $\dot{V}O_{2peak}$ is independent of the method of manipulation, but dependent on changes in blood volume and hyperthermia.

Paragraph Number 33 Whether or not increased SkBF contributes to the decrease in SV associated with CV drift during prolonged exercise is controversial (3). Data suggesting it does (14,27) conflict with data showing that SkBF and SV can change independently (7,11,19,20). The different findings probably reflect differences in subject characteristics and experimental conditions. We did not observe an increase in SkBF over time during 120NF, during which substantial CV drift occurred. Other studies have reported similar findings (19,20). On the other hand, with fluid replacement, we observed an increase in SkBF during the second hour of exercise, which may have contributed to the attenuation of hyperthermia in 120F (13,19,20).

Paragraph Number 34 As far as we are aware, we are the first to report skin blood flow at maximal exercise compared to prior submaximal exercise. This measurement is technically difficult because of the strenuous nature of the exercise and the possibility of movement artifact. As described in the methods, we took special precautions to stabilize and relax the arm and minimize movement artifact, especially at the point of exhaustion during the GXT. Therefore, we do not believe our data reflect movement artifact. In 120NF, T_{re} increased and SkBF decreased at $\dot{V}O_{2peak}$ compared to the 120-min time point. Despite the apparent skin vasoconstriction, $\dot{V}O_{2peak}$ was substantially reduced. The reduction in $\dot{V}O_{2peak}$ probably was due to the reduction in blood volume associated with dehydration coupled with hyperthermia, which causes premature cardiovascular failure (10,23). With fluid ingestion, we also observed decreased SkBF at $\dot{V}O_{2peak}$ compared to the 120-min time point, but because blood volume was not reduced, and T_{re} at $\dot{V}O_{2peak}$ was lower, the vasoconstriction in skin, splanchnic organs and inactive muscles could have prevented a decline in $\dot{V}O_{2peak}$.

Paragraph Number 35 Our main finding that CV drift is linked to a decrease in $\dot{V}O_{2peak}$

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means that CV drift should not be interpreted as a benign response, which can be overcome if exercise intensity is increased, but rather as a response that has important theoretical and practical implications for performance. Because $\dot{V}O_{2peak}$ sets the upper limit on the rate of energy expenditure that can be sustained for a prolonged period of time (28), a decrease in $\dot{V}O_{2peak}$ accompanying CV drift reflects a loss of performance capability over time. The reduction in physical work capacity was reflected in the maximal power output achieved and the duration of the GXT performed immediately after the 120 min of submaximal exercise. Compared to 15NF, there was a 13% decline in PO_{peak} and a 27% decline in time to exhaustion in 120NF.

Paragraph Number 36 Fluid ingestion mitigated CV drift and the associated detrimental effect on $\dot{V}O_{2peak}$ and performance. During 120F, $\dot{V}O_{2peak}$ did not decrease and the decreases in PO_{peak} and time to exhaustion were less than half of those that occurred in 120NF (~5% and ~12%, respectively). Thus, the improvement in performance associated with fluid ingestion during prolonged exercise in a warm environment appears to be mediated, at least in part, via an effect on $\dot{V}O_{2peak}$. Although the ergogenic effect of fluid ingestion, with or without carbohydrates and electrolytes, has long been known (17), the mechanism through which performance is improved has often been difficult to explain, especially in instances in which effects on carbohydrate availability and use could not be demonstrated. Our study demonstrates that fluid ingestion may enhance performance by reducing the detrimental effect of CV drift on $\dot{V}O_{2peak}$.

Paragraph Number 37 The fluid ingested during the 120F trial in our study was a CE sport drink. It is possible that the carbohydrate ingested affected CV drift (13) and performance (18). Blood glucose was higher during 120F than during 120NF and muscle glycogen could have been spared (29), increasing carbohydrate availability. While we cannot rule out these possibilities, they do not affect the tests of our hypotheses and conclusions. Our main objective was to manipulate the degree of CV drift and observe the effect on $\dot{V}O_{2peak}$. Even if carbohydrate ingestion affected the magnitude of CV drift in 120F, it would not negate our conclusions related to the effect of CV drift on $\dot{V}O_{2peak}$. Carbohydrate availability should not affect $\dot{V}O_{2peak}$ if a true

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$\dot{V}O_{2peak}$ limited by cardiovascular capacity is measured, as it appears to have been in this study, as reflected by the similar maximum heart rates under all conditions. The decrease in $\dot{V}O_{2peak}$ caused by CV drift has implications for performance, independent of any effect of carbohydrate ingestion.

Paragraph Number 38 We conclude that the progressive decline in SV during prolonged, constant-rate submaximal exercise in a warm environment, reflective of increased cardiovascular strain associated with hyperthermia, dehydration and other changes that occur over time, reduces $\dot{V}O_{2peak}$. Fluid ingestion improves performance in prolonged exercise, in part, by mitigating the decline in SV and its determinants, and preserving $\dot{V}O_{2peak}$.

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Acknowledgements

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Figure Legends

Figure 1. Skin Blood Flow (SkBF) as a percent ± SEM of 15-min value during submaximal cycling for 120 min with or without fluid ingestion (120F and 120NF) and at $\dot{V}O_{2peak}$. [†]Significantly different from 15-min value, $P < 0.05$; **Significantly different from 120-min value, $P < 0.05$.

Figure 2. Percent change in mean ± SEM $\dot{V}O_{2peak}$ (top graph) and peak power output (PO_{peak}, bottom graph) from 15NF, measured after 60 min or 120 min of cycling without fluid ingestion, or after 120 min of cycling with fluid ingestion (60NF, 120NF, 120F). [†]Significantly different from 15NF, $P < 0.05$; *Significantly different from 60NF, $P < 0.05$, [‡]Significantly different from 120NF, $P < 0.05$.

Figure 3. Relation of $\dot{V}O_2$, heart rate (HR), O_2 pulse, and rectal temperature (T_{re}) to power output during the graded exercise tests immediately after submaximal exercise during the experimental trials. [†]Significantly different from 15NF, $P < 0.05$; *Significantly different from 60NF, $P < 0.05$, [‡]Significantly different from 120NF, $P < 0.05$.

Table 1

1

Table 1: Responses to submaximal exercise of different durations with and without fluid ingestion. Values are means ± SD.

Variable	No Fluid			Fluid		
	15-min	60-min	120-min	15-min	60-min	120-min
$\dot{V}O_2$, $l \cdot min^{-1}$	2.48 ± 0.24	2.56 ± 0.24	2.63 ± 0.23[†]	2.53 ± 0.18	2.63 ± 0.19	2.66 ± 0.21[†]
$\dot{Q}$, $l \cdot min^{-1}$	16.0 ± 1.5	16.1 ± 1.6	15.7 ± 1.8	16.4 ± 1.4	16.9 ± 1.0[‡]	17.0 ± 1.1[‡]
SV, ml	115 ± 15	110 ± 14	99 ± 13[†*]	115 ± 15	115 ± 10	112 ± 10[‡]
HR, bpm	140 ± 10	148 ± 12[†]	159 ± 15[†*]	143 ± 10	147 ± 9[†]	153 ± 9[†*]
O_2 Pulse, $ml \cdot b^{-1}$	17.8 ± 1.9	17.3 ± 1.6[†]	16.6 ± 1.5[†*]	17.8 ± 1.8	17.9 ± 1.7	17.4 ± 1.4
Blood Lactate, $mmol \cdot l^{-1}$	1.3 ± 0.05	1.2 ± 0.04	1.3 ± 0.04	1.7 ± 0.06	1.5 ± 0.04	1.3 ± 0.03
Blood Glucose, $mmol \cdot l^{-1}$	4.4 ± 0.6	5.0 ± 0.5[†]	4.7 ± 0.5[*]	4.1 ± 0.6	5.8 ± 0.9[†]	5.3 ± 0.9[‡]
PV, % Δ from rest	-6.1 ± 2.6	-7.3 ± 3.8	-8.9 ± 4.2[†*]	-6.2 ± 2.7	-4.5 ± 4.7	-6.0 ± 5.0
$\overline{T}_{sk}$ (°C)	34.1 ± 0.7	34.0 ± 1.1	33.5 ± 1.4	34.4 ± 0.6	34.1 ± 1.0	33.9 ± 1.3
T_{re}, (°C)	37.7 ± 0.3	38.4 ± 0.2[†]	38.8 ± 0.2[†*]	37. 7 ± 0.2	38.3 ± 0.3[†]	38.5 ± 0.3[†*‡]
RPE	10.0 ± 2.4	11.5 ± 2.3[†]	13.2 ± 2.0[†*]	10.0 ± 2.3	11.6 ± 1.6[†]	12.6 ± 1.7[†*]

$\dot{V}O_2$, oxygen uptake; $\dot{Q}$, cardiac output; SV, stroke volume; HR, heart rate; PV, plasma volume; $\overline{T}_{sk}$, mean skin temperature; T_{re}, rectal temperature; RPE, rating of perceived exertion.

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[†]Significantly different from 15-min value, $P < 0.05$; [*]Significantly different from 60-min value, $P < 0.05$; [‡]Significantly different from No-Fluid Condition at the same time point, $P < 0.05$.

Table 2

Table 2: Responses to peak exercise following submaximal exercise of different durations with and without fluid ingestion. Values are means ± SD.

Variable	Control	15NF	60NF	120NF	120F
$\dot{V}O_2$, $l{\cdot}min^{-1}$	4.32 ± 0.31	4.33 ± 0.43	4.28 ± 0.47	3.94 ± 0.41[†]	4.24 ± 0.44[‡]
$\dot{V}O_2$, $ml{\cdot}kg^{-1}{\cdot}min^{-1}$	57.78 ± 6.67	58.08 ± 7.74	57.76 ± 8.81	52.95 ± 6.59[†]	56.75 ± 5.97[‡]
$\dot{V}_E$ (STPD), $l{\cdot}min^{-1}$	133.7 ± 14.4	131.1 ± 18.1	132.6 ± 18.9	120.9 ± 24.1[†*]	131.2 ± 15.0[‡]
RER	1.15 ± 0.04	1.13 ± 0.04	1.11 ± 0.03	1.04 ± 0.09[†*]	1.07 ± 0.04
HR, bpm	187 ± 10	185 ± 10	188 ± 11	185 ± 10	187 ± 9
O_2 Pulse, $ml{\cdot}b^{-1}$	——	23.9 ± 2.8	23.1 ± 2.8	21.6 ± 2.8[†]	23.1 ± 2.6
Blood Lactate, $mmol{\cdot}l^{-1}$	8.9 ± 1.0	7.9 ± 1.2	6.8 ± 1.3	5.4 ± 1.5[†*]	6.5 ± 0.9[‡]
PV, % Δ from rest	——	-14.0 ± 2.4	-13.6 ± 3.0	-14.8 ± 3.6	-11.9 ± 3.4
$\bar{T}_{sk}$ (°C)	——	34.2 ± 0.5	33.8 ± 1.0	33.1 ± 1.3	33.8 ± 1.3[‡]
T_{re}, (°C)	——	38.1 ± 0.2	38.6 ± 0.2[†]	38.9 ± 0.2[†*]	38.6 ± 0.2[‡]
RPE	18.7 ± 0.9	19.2 ± 0.6	19.0 ± 0.4	19.3 ± 0.5	19.3 ± 0.6
Test Duration, min	11.4 ± 2.2	12.1 ± 1.3	10.7 ± 1.6[†]	8.8 ± 2.2[†*]	10.7 ± 1.9[‡]
Power Output, watts	330 ± 25	332 ± 27	307 ± 37[†]	290 ± 34[†*]	317 ± 38[‡]
Decrease in Body Mass, %	——	1.3 ± 0.3	2.3 ± 0.4[†]	3.7 ± 0.6[†*]	0.7 ± 0.5[‡]

$\dot{V}O_2$, oxygen uptake; $\dot{V}_E$, minute ventilation; RER, respiratory exchange ratio; HR, heart rate; PV, plasma volume; $\overline{T}_{sk}$, mean skin temperature; T_{re}, rectal temperature; RPE, rating of perceived exertion; [†]Significantly different from 15NF, $P < 0.05$; [*]Significantly different from 60NF, $P < 0.05$; [‡]Significantly different from 120NF, $P < 0.05$.

Figure 1
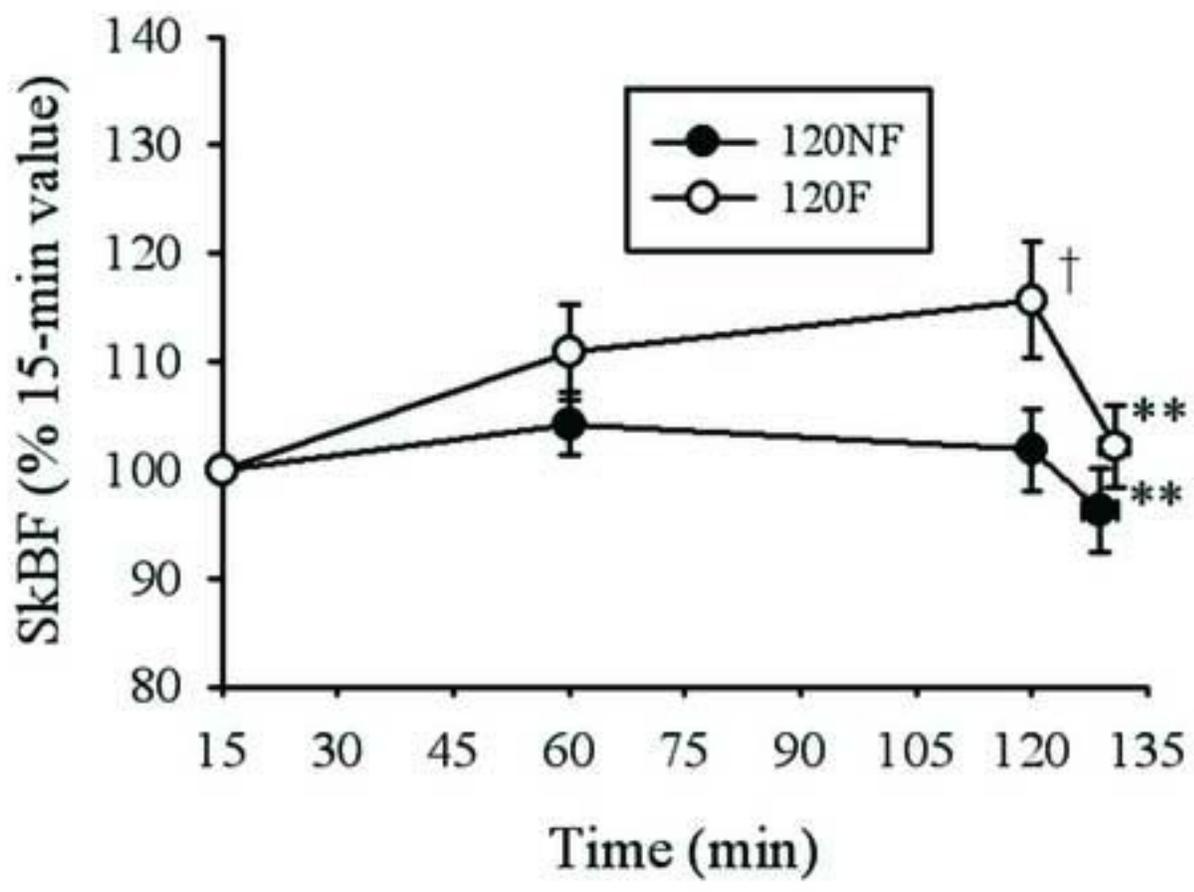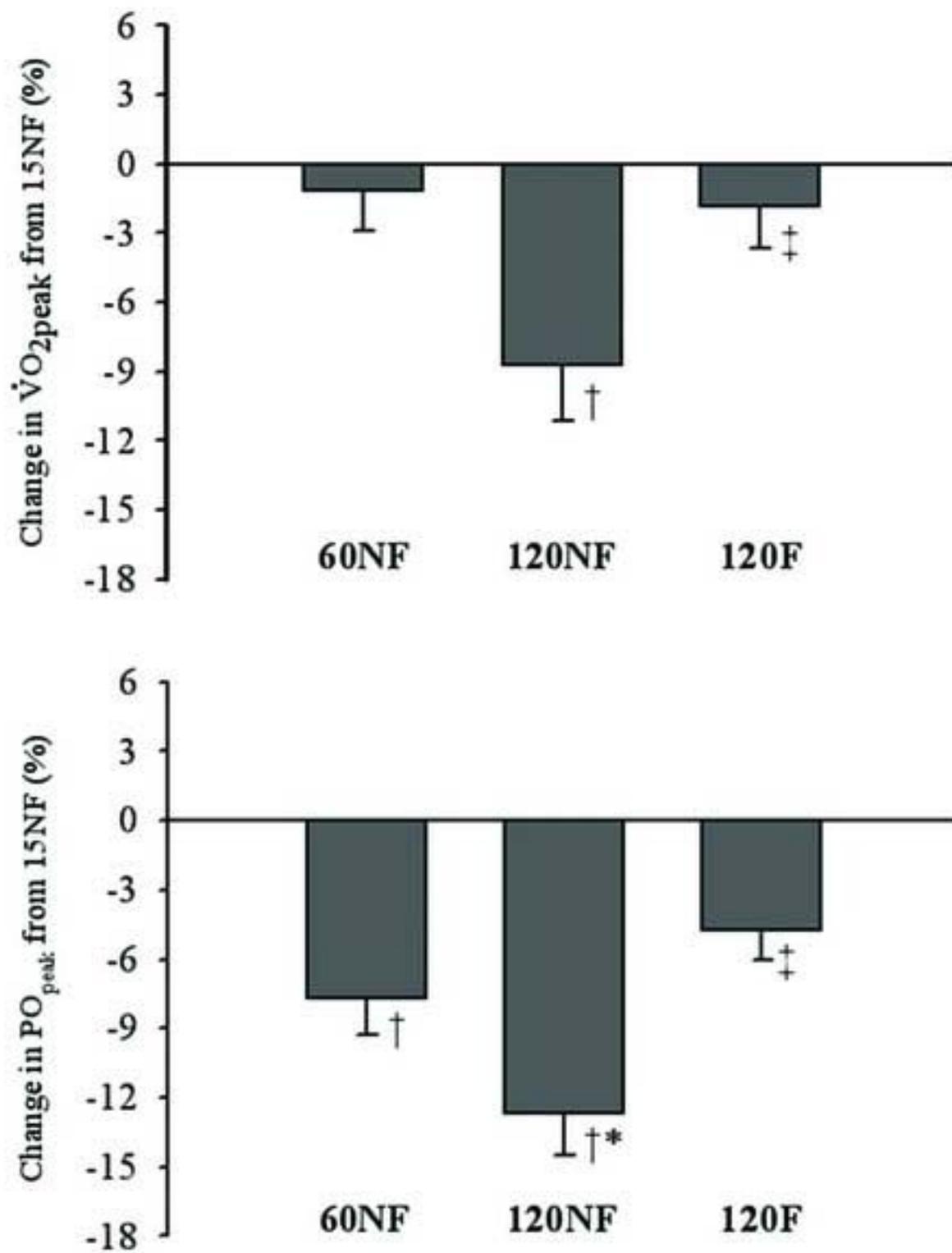**Click here to download high resolution image**

Figure 3
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