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## Human thermoregulatory function during exercise and immersion after 35 days of horizontal bed-rest and recovery

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**Abstract** The present study evaluated the effect of 35 days of experimental horizontal bed-rest on exercise and immersion thermoregulatory function. Fifteen healthy male volunteers were assigned to either a Control ( $n = 5$ ) or Bed-rest ( $n = 10$ ) group. Thermoregulatory function was evaluated during a 30-min bout of submaximal exercise on a cycle ergometer, followed immediately by a 100-min immersion in 28°C water. For the Bed-rest group, exercise and immersion thermoregulatory responses observed post-bed-rest were compared with those after a 5 week supervised active recovery period. In both trials, the absolute work load during the exercise portion of the test was identical. During the exercise and immersion, we recorded skin temperature, rectal temperature, the difference in temperature between the forearm and third digit of the right hand ( $\Delta T_{\text{forearm-fingertip}}$ )— an index of skin blood flow, sweating rate from the forehead, oxygen uptake and heart rate at minute intervals. Subjects provided ratings of temperature perception and thermal comfort at 5-min intervals. Exercise thermoregulatory responses after bed-rest and recovery were similar. Subjective ratings of temperature perception and thermal comfort during immersion indicated that subjects perceived similar combinations of Tsk and Tre to be warmer and thermally less uncomfortable after bed-rest. The average

(SD) exercise-induced increase in Tre relative to resting values was not significantly different between the Post-bed-rest (0.4 (0.2)°C) and Recovery (0.5 (0.2)°C) trials. During the post-exercise immersion, the decrease in Tre, relative to resting values, was significantly ( $P < 0.05$ ) greater in the Post-bed-rest trial (0.9 (0.5)°C) than after recovery (0.4 (0.3)°C).  $\Delta T_{\text{forearm-fingertip}}$  was 5.2 (0.9)°C and 5.8 (1.0)°C at the end of the post-bed-rest and recovery immersions, respectively. The gain of the shivering response (increase in  $\dot{V}O_2$  relative to the decrease in Tre;  $\dot{V}O_2/\text{Tre}$ ) was 1.19 l min<sup>-1</sup>°C<sup>-1</sup> in the Recovery trial, and was significantly attenuated to 0.51 l min<sup>-1</sup>°C<sup>-1</sup> in the Post-bed-rest trial. The greater cooling rate observed in the post-bed-rest trial is attributed to the greater heat loss and reduced heat production. The former is the result of attenuated cold-induced vasoconstriction and enhanced sweating rate, and the latter a result of a lower shivering  $\dot{V}O_2$  response.

**Keywords** Space · Thermoregulation · Bed-rest · Spaceflight

### Introduction

Results of a limited number of thermal studies on spaceflight missions suggest a decrease in the sensitivity of the heat loss responses in humans (Fortney et al. 1998) and primates (Sulzman et al. 1992). This has been confirmed by bed-rest and post-flight experiments, noting that inactivity or prolonged exposure to microgravity causes impairment in exercise thermoregulation (Fortney 1987; Crandall et al. 1994; Lee et al. 2002). Specifically, there is a greater exercise-induced increase in core temperature (Greenleaf and Reese 1980; Greenleaf 1989), attributed to impaired sweating (Greenleaf and Reese 1980; Fortney 1987; Fortney et al. 1998; Lee et al. 2002) and vasodilatory responses (Williams and Reese 1976; Crandall et al. 1994; Fortney et al. 1998; Lee et al. 2002). These alterations in exercise thermoregulatory responses

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have been attributed to non-thermal factors associated with prolonged bed-rest.

The reported changes in the sweating and vasodilatory responses following bed-rest are most likely attributable to the changes in body fluid compartments. Namely, it is well documented that both hypovolemia and dehydration, conditions present in subjects during various phases of bed-rest, attenuate the magnitudes of the vasodilatory and sweating responses. Hypovolemia has been demonstrated by Fortney et al. (1981) to significantly attenuate the sweating response. Specifically, an 8% decrease in blood volume significantly reduced the magnitude of the exercise sweating response and attenuated the gain of the sweating response relative to increases in core temperature. This reduction in the  $E_{sw}/T_{es}$  response was observed only on the skin of non-exercising regions. The sweating response did not appear to be affected in the exercising regions.

Similar to the effect of hypovolemia, dehydration also attenuates the sweating response (Ekblom et al. 1970; Candas et al. 1986; Grucza et al. 1987). It is the increased plasma osmolality, associated with dehydration, that is sensed by hypothalamic osmosensitive neurons (Silva and Boulant 1984), that in turn modulate the thermoregulatory responses (Baker and Doris 1982 a, b). In the event that the conditions of dehydration and hypovolemia occur concomitantly, then the effect on thermoregulatory responses has been reported to be additive (Fortney et al. 1981; Baker 1984).

Fortney (1987) has noted that the alterations in thermoregulation during bed-rest are also evident in euhydrated normovolemic subjects, suggesting that some other factors involved in the bed-rest-induced deconditioning are responsible for the attenuation of the heat loss response. It is well documented that exercise conditioning or training decreases the core temperature threshold for sweating and increases the gain of the sweating response (Taylor 1986; Fortney and Vroman 1985; Gleeson 1998). Deconditioning may, therefore, reverse these alterations, causing an attenuated exercise heat loss response, consequently potentiating the elevation in core temperature during post-bed-rest exercise. The observed alterations in temperature regulation after prolonged bed-rest would then be due not only to the effects of fluid volume reductions, but also to other manifestations of bed-rest-induced deconditioning.

Despite mounting evidence of impaired thermoregulation during exercise and exposure to heat following bed-rest, no studies have examined the effect of bed-rest on thermoregulatory responses initiated to maintain deep body temperature in a high heat loss environment. This was the principal aim of the present study.

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## Materials and Methods

Studies investigating the effect of prolonged bed-rest on physiological responses normally compare values

observed before, with those observed immediately after bed-rest. In contrast to this approach, we compared the thermoregulatory responses observed following complete recovery with those observed immediately after bed-rest. The reason for this was that one of the objectives of the protocol was to achieve an exercise-induced elevation in core temperature, initiated by submaximal cycle ergometry conducted at identical absolute work loads in both trials, since the magnitude of the exercise-induced increment in core temperature is a function of the absolute work load (Eiken and Mekjavic 2004). However, for any given absolute work load, bed-rest will cause an increase in the relative work. It is not possible to predict an absolute work load for the submaximal exercise, which would not cause the relative work to increase towards maximal levels after bed-rest, and thus limit the duration of the exercise. Consequently, we regulated the absolute work load in the Post-bed-rest trials at a level which resulted in an exercising heart rate observed at 50% of pre-bed-rest maximal work load. The same absolute work load was then replicated in the exercise portion of the trial after full recovery.

The exercise and immersion thermoregulatory responses immediately following bed-rest were compared with those observed after a 5-week active recovery. In both trials, subjects exercised at identical absolute work loads during the exercise portion of the test.

## Subjects

Healthy male volunteers ( $n = 15$ ) were assigned to either a Control ( $n = 5$ ) or Bed-rest group ( $n = 10$ ). Their participation in the study was subject to physician's approval. Following familiarization with the study protocol and instrumentation, subjects gave their written consent to participate in the study. The protocol of the study was approved by the National Ethics Committee (Ministry of Health) of Slovenia and was performed according to the Declaration of Helsinki. Subjects were aware that they could discontinue their participation in the study at any time.

## Protocol

Subjects in the Bed-rest group were hospitalized (five subjects to a room) at the Orthopaedic Hospital Val-doltra (Ankaran, Slovenia). The Control group of subjects conducted the same experiments at the same time and time intervals as the Bed-rest group. In contrast to the Bed-rest group, subjects in the Control group remained ambulatory and continued unrestricted with their normal daily activities. Both Control and Bed-rest subjects' physical characteristics (mass, height, skinfold thickness), maximal aerobic capacity ( $\dot{V}O_{2max}$ , maximum work rate), and strength (handgrip, hip extensors, knee extensors, jump test) were determined prior to the

onset of the bed-rest period, immediately after the 5-week bed-rest, and after 5 weeks of active recovery.

An estimate of total body fat was derived with the formula of Durnin and Womersely (1974) based on the measurements of skinfold thickness (TB, Sportna Oprema, Slovenia) at four sites.

For the measurement of maximum voluntary contraction (MVC) of the knee extensors, subjects were seated on a bench, such that neither leg was in contact with the floor, and the resting knee angle was 90°. The subjects' upper torso and thighs were immobilized with straps. A strap fastened around their right ankle was connected to a force transducer. During the contraction, the subjects held their arms crossed at the chest level. For the determination of MVC of the hip extensors, subjects lay prone on a bench. Only their upper torso was on the bench, so that the resting hip angle was 90°. Their torso was immobilized with straps, and a strap fastened around their lower thigh (just above the knee) was connected to a force transducer. Prior to, and during the MVC of hip extensors, the subjects' calf was supported, to prevent any involvement of knee extensors. Subjects conducted a series of five MVCs of the hip and knee extensors, with a 2-min break between contractions. Five trials were also made during the measurement of handgrip. The best result of the MVC and handgrip tests were used in the analysis.

During the 35-day bed-rest period, subjects were under 24-h care, and their daily well-being monitored by the hospital staff. During this period, subjects were requested to maintain a horizontal position at all times, and not to perform any exercises (i.e. undue isometric contractions). All activities were performed in the horizontal position. Subjects could support themselves on their elbows during eating, personal hygiene and transfer between bed and gurney. In addition, they were requested not to use more than one pillow for head support at all times, and when using a pillow, to ensure that their shoulders were not supported. During the bed-rest, regular weekly ultrasonic surveillance of the lower limb veins was conducted, to monitor for deep vein thrombosis. In addition, infra-red thermograms of the lower limbs were also obtained at weekly intervals. Twice weekly subjects received extensive physiotherapy, which comprised passive movements of all joints and light massage of the neck and lower back regions. Active muscle contractions were avoided. Subjects received physiotherapy also on request, at any time.

Bed-rest subjects' dietary intake was not monitored. All ate regular hospital meals, and drank non-alcoholic beverages ad libitum.

To assess thermoregulatory function we adapted the methodology reported previously (Mekjavic et al. 1991). Following a 5-min rest period, subjects performed a 30-min bout of submaximal upright exercise on a cycle ergometer. The work load was maintained at a level, which resulted in an exercising heart rate observed at 50% of pre-bed-rest maximal work load. The temperature of the room during the exercise was maintained at

26°C. Immediately following the exercise, subjects were transferred to an adjacent tank of well-stirred water maintained at 28°C. They remained immersed to the manubrium in a semi-reclining position for 100 min. During the exercise and immersion periods, we monitored oxygen uptake ( $\dot{V}O_2$ , l min<sup>-1</sup>), skin (Tsk, °C) and rectal temperatures (Tre, °C), and forehead sweating rate (Esw, g m<sup>-2</sup> min<sup>-1</sup>). Peripheral vasomotor tone was assessed from the difference in temperature of the skin of the forearm and tip of the third digit ( $\Delta T_{\text{forearm-fingertip}}$ , °C) of the right hand (Rubinstein and Sessler 1990). Consequently, the right hand was not submerged during the immersion period, but was suspended at the level of the water. During the exercise and immersion phases of the trials, subjects wore lightweight running shorts. Subjects were also requested to provide subjective ratings of temperature perception (7-point scale: 1, cold; 2, cool; 3, slightly cool; 4, neutral; 5, slightly warm; 6, warm; 7, hot) and thermal comfort (4-point scale: 1, comfortable; 2, slightly uncomfortable; 3, uncomfortable; 4, very uncomfortable) at 5-min intervals.

Upon completion of the bed-rest, the bed-rest subjects participated in a 5-week active recovery programme, which comprised a minimum of 3 weekly 1 h supervised sessions of strength training and/or cycle ergometry. After this active recovery period, their physical characteristics, strength and aerobic capacity were again determined.

## Instrumentation

Maximum voluntary contraction of the knee and hip extensors was measured with a force transducer (Nobel Elektronik Force Transducer Type KRG-4, Karskoga, Sweden). Handgrip strength was measured with a Baseline Hydraulic hand dynamometer (FEI Irvington, NY, USA).

During the exercise and immersion trials, subjects breathed via a low resistance oro-nasal mask (Hans Rudolf, MO, USA). Inspired minute ventilation ( $\dot{V}_I$ , l min<sup>-1</sup>) was determined with a turbine ventilation module (KL Engineering, CA, USA). The expiratory side of the oro-nasal mask was connected via corrugated respiratory hosing to a 9-l fluted Plexiglas mixing box. A sample of the mixed expired gas was continuously drawn from the mixing box at a rate of 0.2 l min<sup>-1</sup> and analysed for oxygen (Applied Electrochemistry model S-3A/II oxygen analyser, Pittsburgh, PA, USA) and carbon dioxide (Siemens model Ultramat 22P carbon dioxide analyser, Germany) contents.

Unweighted average skin temperature (Tsk, °C) was determined from measurements obtained with model YSI 409AC skin thermistors (Yellow Springs Instruments, Yellow Springs, OH, USA) at four sites: arm (lateral aspect of upper arm), chest (right lateral mid-clavicular line at the third intercostal spacing), thigh (anterior surface of the mid thigh), calf (upper lateral aspect of the calf). Rectal temperature was measured

with a rectal thermistor (Yellow Springs Instruments) placed within a protective sheath and inserted 10 cm beyond the anal sphincter. For determination of peripheral vasomotor tone, we measured the temperature of the skin of the forearm and tip of the third digit ( $\Delta T_{\text{forearm-fingertip}}$ ) with YSI 409AC thermistors.

Sweating rate ( $E_{\text{sw}}$ ,  $\text{g m}^{-2} \text{min}^{-1}$ ) during the test of thermoregulatory function was measured from the forehead with a ventilated capsule (surface area covered by capsule was  $467 \text{ mm}^2$ ). Constant flow of air at a rate of  $0.8 \text{ l min}^{-1}$  through the capsule was ensured with flow meters at the inlet and outlet of the capsule (Perflow Instruments Ltd, London, UK). The temperature and humidity of the air entering and exiting the capsule was measured with thermistors and resistance hygrometers. The rate of sweating was determined from the difference in water vapour content of the outflowing and inflowing air, adjusting for the surface area of the ventilated capsule.

All sensors were factory calibrated and recalibrated prior to each trial. All temperature and respiratory measurements were recorded on-line at minute intervals with a data acquisition system (Biopac Systems Inc., Santa Barbara, CA, USA) controlled by AcqKnowledge software (Biopac Systems Inc.) on a Macintosh computer (Apple, Cupertino, CA, USA). Oxygen uptake ( $\dot{V}O_2$ , expressed in  $\text{l min}^{-1}$ ) was calculated at minute intervals during the rest, exercise and immersion phases of all trials. Heart rate was measured at minute intervals with a Polar heart rate monitor (Finland). Subjects provided ratings of temperature perception and thermal comfort at 5-min intervals.

The average thermoregulatory responses observed post-bed-rest and recovery in the Bed-rest group, and over the same time period in the Control group, were compared with a one-way repeated measures ANOVA. Subjective ratings of temperature perception and thermal comfort were analysed with a Wilcoxon non-parametric test. The 5% level ( $P < 0.05$ ) was chosen as statistically significant.

**Table 1** Physical characteristics (mass, body fat), aerobic work capacity ( $\dot{V}O_{2\text{max}}$ , maximum work rate), muscle strength (MVC: hand grip, hip extensors, knee extensors) and muscle function

	Control Group			Bed-rest Group				
	Pre	Post	Pre versus Post ( <i>P</i> )	Pre BR	Post BR	Recovery	Pre BR versus Post BR ( <i>P</i> )	Pre BR versus Recovery ( <i>P</i> )
Mass(kg)	71.5(22.3)	72.2(23)	<i>NS</i>	70.1(7.7)	67.8(7.3)	69.6(8.5)	0.003	<i>NS</i>
Body fat(%)	16.4(5.4)	15.7(4.5)	<i>NS</i>	17.6(5.4)	17.7(6.1)	16.8(6.2)	<i>NS</i>	<i>NS</i>
$\dot{V}O_{2\text{max}}$ ( $\text{l min}^{-1}$ )	2.8(0.6)	3.1(1.1)	<i>NS</i>	2.8(0.8)	2.3(0.4)	2.9(0.7)	0.02	<i>NS</i>
WRmax(W)	252(53)	260(48)	<i>NS</i>	257(44)	212(37)	258(44)	0.0005	<i>NS</i>
Handgrip(kg)	53.6(7.1)	59.2(7.2)	<i>NS</i>	47.9(8.8)	47.3(9.4)	50.3(9.6)	<i>NS</i>	<i>NS</i>
Hip ext.(kg)	148.8(38.1)	138(33.9)	<i>NS</i>	132.8(28.5)	103.2(18.8)	126.5(27.6)	0.0008	<i>NS</i>
Knee ext.(kg)	65.0(11.1)	64.2(10.8)	<i>NS</i>	61.6(6.5)	51.2(4.2)	63.6(9.1)	0.0007	<i>NS</i>
Jump test(m)	0.79(0.03)		<i>NS</i>	0.78(0.09)	0.74(0.1)	0.76(0.1)	0.019	<i>NS</i>

Note: with the exception of the Recovery trial, Control subjects were tested at the same time as bed-rest subjects  
*NS* not statistically significant; *P* calculated *P* value

## Results

All subjects in the Bed-rest group completed the 35-day horizontal Bed-rest. All Control subjects reported that they had maintained similar daily activities through the study period. Over the 35-day period corresponding to bed-rest, and the 35 day period corresponding to the recovery phase, we observed no significant changes in the physical characteristics, aerobic capacity, muscle strength and characteristics of the exercise and immersion thermoregulatory responses in the ambulatory Control group of subjects. Therefore, only the results of the Bed-rest group will be presented.

### Physical characteristics, aerobic work capacity and muscle strength

After the bed-rest, there was a significant decrease ( $P < 0.005$ ) in subjects' average (SD) mass from 70.1 (7.7) kg to 67.8 (7.3) kg, and an increase ( $P < 0.05$ ) in height from 1.79 (0.09) m to 1.80 (0.09) m. Maximum oxygen uptake decreased from 2.79 (0.76)  $\text{l min}^{-1}$  in the Pre-bed-rest trial to 2.29 (0.36)  $\text{l min}^{-1}$  post-bed-rest, which was also reflected in a decrease ( $P < 0.001$ ) in maximum work rate from 257 (44) W pre-bed-rest to 212 (37) W post-bed-rest. Strength of the hip and knee extensors also decreased, whereas there was no change in handgrip. As evident in Table 1, these significant bed-rest-induced changes in physical characteristics, aerobic capacity and muscle strength were redressed following the 5-week programme of active recovery.

### Exercise

Unweighted mean skin temperature increased from a resting level of 33.3 (2.7)°C to 34.3 (2.6)°C by the end of the exercise in the Post-bed-rest trial, and from 34.0 (2.3)°C to 34.3 (2.5)°C in the Recovery trial.

(jump test) in Control and Bed-rest subjects, before (Pre) and after (Post) the 35 days of horizontal bed-rest and after 5 weeks of active recovery (Recovery)



The exercise-induced elevation in  $T_{re}$  was similar in the Post-bed-rest and Recovery trials (Fig. 1a). Average (SD)  $T_{re}$  increased from resting levels of 36.5 (0.2) in the Post-bed-rest trial and 36.1 (0.2) in the Recovery trial, to asymptotic values of 37.0 (0.4) and 36.5 (0.3), respectively.

There was no significant difference in the exercise  $E_{sw}$  response between the Post-bed-rest and Recovery trials (Fig. 1b). Skin blood flow, as reflected in the resting  $\Delta T_{forearm-fingertip}$  (Fig. 1c) was greater in the Post-bed-rest trial, and increased progressively in both trials during exercise.  $\Delta T_{forearm-fingertip}$  decreased from 0.3 (5.1) $^{\circ}\text{C}$  to  $-1.7$  (0.7) $^{\circ}\text{C}$  in the Recovery trial. In the Post-bed-rest trial,  $\Delta T_{forearm-fingertip}$  decreased from  $-1.52$  (3.3) $^{\circ}\text{C}$  to  $-2.6$  (1.4) $^{\circ}\text{C}$  by min 20, and thereafter returned to pre-exercise levels.

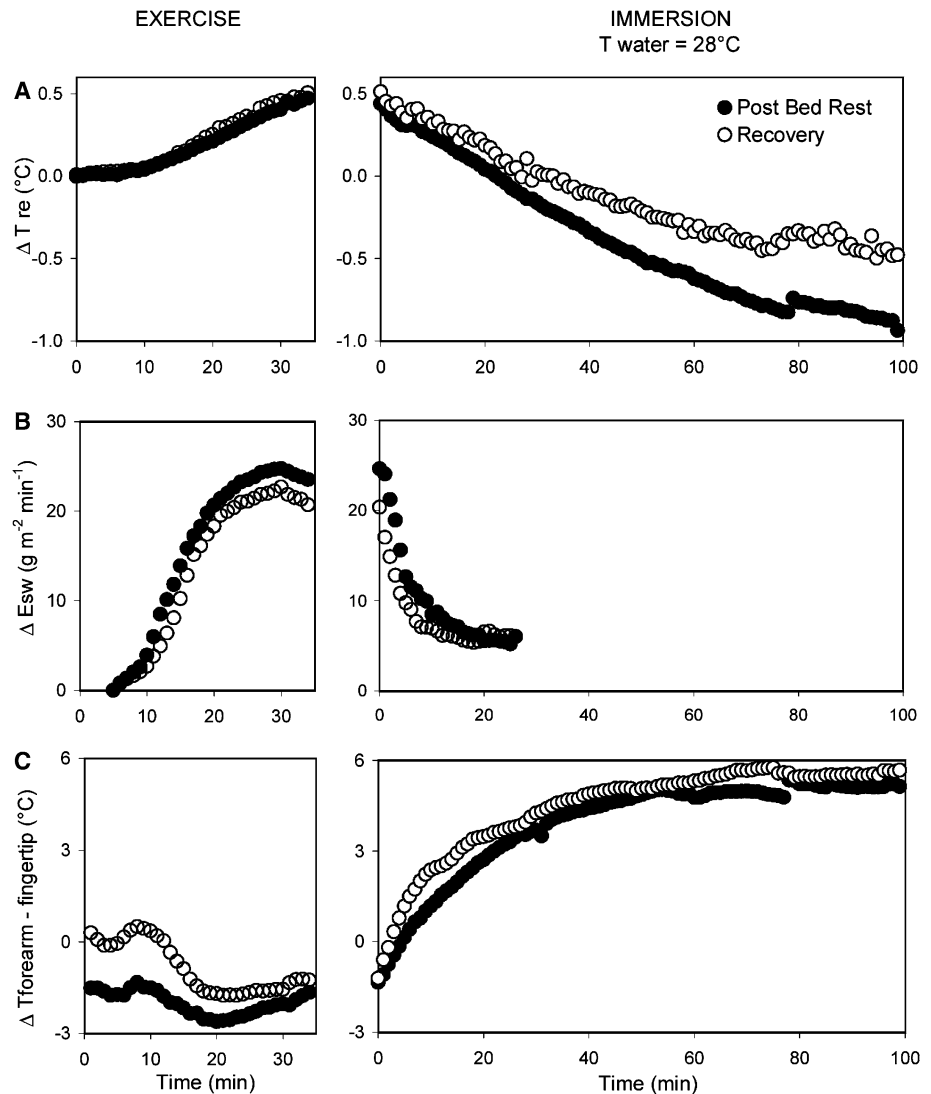
### Immersion

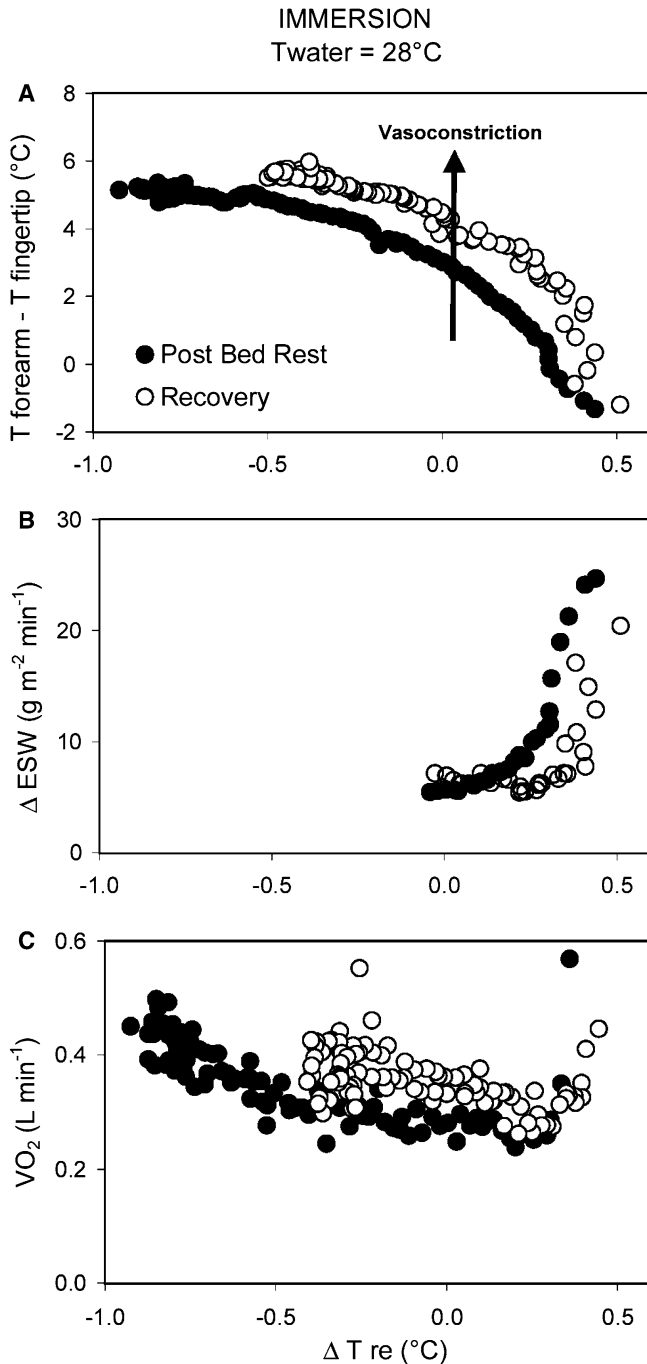
Average unweighted  $T_{sk}$  was clamped at identical levels in both trials, stabilizing at 29.0 (4.1) $^{\circ}\text{C}$  by the end of the immersion in both the Post-bed-rest trial and in the Recovery trials. Subjects exhibited a significantly greater

decrement ( $P < 0.005$ ) in  $T_{re}$  in the Post-bed-rest trial (Fig. 1b). Following the 0.4 (0.2) $^{\circ}\text{C}$  exercise-induced increase in  $T_{re}$  relative to resting values in the Post-bed-rest trial,  $T_{re}$  decreased by 0.9 (0.5)  $^{\circ}\text{C}$ . In the Recovery trial,  $T_{re}$  increased by 0.5 (0.2)  $^{\circ}\text{C}$  at the end of the exercise, and thereafter decreased by 0.4 (0.2)  $^{\circ}\text{C}$  relative to resting values at the end of the immersion. There was therefore a 60% increase in  $T_{re}$  cooling rate after bed-rest, (0.8 $^{\circ}\text{C h}^{-1}$ ) compared to that observed after full recovery (0.5 $^{\circ}\text{C h}^{-1}$ ). It may be assumed that during this particular protocol, the spatial differences in core temperature are minimal (Mekjavic et al. 1991) during the immersion phase.

Immediately upon immersion, sweating decreased rapidly from similar post-exercise levels in both trials, and abated by minute 30 of immersion (Fig. 1b). Overall,  $E_{sw}$  was significantly higher ( $P < 0.05$ ) during the immersion phase of the Post-bed-rest trial, but there was no significant difference in either the  $\Delta E_{sw}/\Delta T_{re}$  ratio, nor in the rectal temperature thresholds for the cessation of sweating between the two trials (Fig. 2b). Concomitant with the decreasing rate of

**Fig. 1** Relative change in average rectal temperature (A  $T_{re}$ ), sweating rate (B  $\Delta E_{sw}$ ) and the difference in skin temperature between the forearm and fingertip, an index of skin blood flow (C  $\Delta T_{forearm-fingertip}$ ) during the exercise and immersion in the Post-bed-rest and Recovery trials. The discontinuity occurring at minute 79 (in panels A and C) is due to one subject requesting termination of the immersion





**Fig. 2** **A** The difference in skin temperature between the forearm and fingertip, an index of skin blood flow ( $\Delta T_{\text{forearm-fingertip}}$ ) plotted as a function of the relative change in rectal temperature ( $\Delta T_{\text{re}}$ ) during the immersion phase only. The attenuated response in the Post-bed-rest trial suggests an attenuation of the cold-induced vasoconstriction. **B** The relative sweating response ( $\Delta E_{\text{sw}}$ ) as a function of  $\Delta T_{\text{re}}$  during immersion. **C** The oxygen uptake response during the post-exercise immersion as a function of  $\Delta T_{\text{re}}$ . Following the rapid post-exercise decrease in  $\dot{V}O_2$  towards resting levels, there is a progressive increase in  $\dot{V}O_2$  with decreasing  $\Delta T_{\text{re}}$ . The gain of the  $\dot{V}O_2/\Delta T_{\text{re}}$  response is attenuated in the Post-bed-rest trial, reflecting an attenuation of shivering thermogenesis

sweating there was a decrease in skin blood flow, as indicated by  $\Delta T_{\text{forearm-fingertip}}$  (Fig. 2a). There was a significantly smaller cold-induced vasoconstrictor response in the Post-bed-rest compared to the Recovery trial (Fig. 2a), as reflected in the end-immersion  $\Delta T_{\text{forearm-fingertip}}$  values, which were 5.2 (0.9)°C and 5.8 (0.9)°C for the Post-bed-rest and Recovery trials, respectively.

Shivering thermogenesis, reflected in the oxygen uptake response, was significantly ( $P < 0.05$ ) attenuated during the Post-bed-rest immersion compared to the Recovery immersion trial (Fig. 2c). Despite the more than twofold decrement in  $T_{\text{re}}$  from resting level in the Post-bed-rest trial ( $\Delta T_{\text{re}} = -0.9$  (0.5)°C) compared to the Recovery trial ( $\Delta T_{\text{re}} = 0.4$  (0.3)°C), shivering thermogenesis, reflected in the  $\dot{V}O_2$  response, was similar in both trials. End-immersion  $\dot{V}O_2$  was 0.4 (0.1) l min<sup>-1</sup> in both the Post-bed-rest and Recovery trials. The gain of the shivering response, defined as the  $\dot{V}O_2$  response to a decrement in  $T_{\text{re}}$  ( $\Delta \dot{V}O_2/\Delta T_{\text{re}}$ ), was 1.19 l min<sup>-1</sup>°C<sup>-1</sup> in the Post-bed-rest trial and 0.51 l min<sup>-1</sup>°C<sup>-1</sup> in the Recovery trial.

At any given core temperature during the immersion in 28°C water, subjects perceived the Post-bed-rest to be warmer (Fig. 3a) and thermally less uncomfortable (Fig. 3b) in trial.

## Discussion

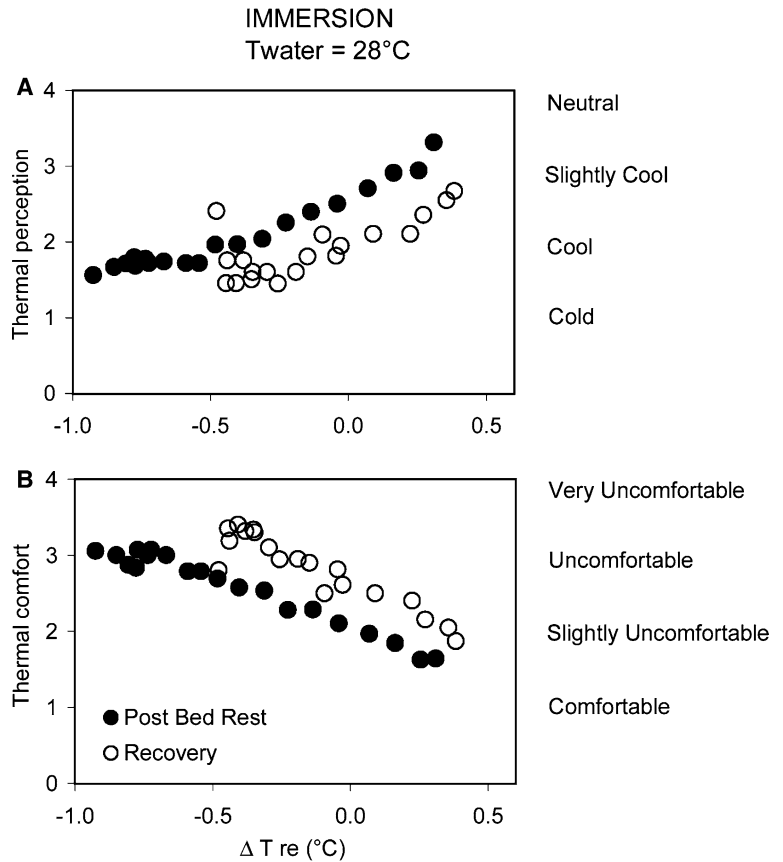
The magnitude of the observed differences in subjects' physical characteristics, aerobic work capacity, muscle strength and function agree with observations reported by other investigators for bed-rest exposures (see also review by Fortney et al. 1996) and space flights (see also review by Convertino 1996) of similar duration. This confirms that subjects adhered to the requested bed-rest regimen for the duration of the study.

The main finding of the present study is that prolonged (35 days) horizontal bed-rest did not affect exercise temperature regulation, but altered thermal balance during immersion. Since no significant differences in exercise and immersion thermoregulatory responses were observed in the Control group of subjects over the same time period, we attribute the observed greater decrement in  $T_{\text{re}}$  during immersion in 28°C primarily to a bed-rest-induced attenuation of cold-induced vasoconstriction and the shivering response.

### Exercise temperature regulation

The post-bed-rest thermoregulatory tests were conducted on the second day of recovery, and it is therefore likely that any changes in thermoregulation associated with the bed-rest-induced reduction in plasma volume

**Fig. 3** The median subjective ratings of thermal perception and thermal comfort during the immersion in 28°C water as a function of the change in  $\Delta T_{re}$ . For similar combinations of  $T_{sk}$  and  $\Delta T_{re}$ , subjects perceived to be warmer and less uncomfortable during the Post-bed-rest trials



would be less prominent, due to the fairly rapid recovery of plasma volume following the cessation of bed-rest (Fortney et al. 1991). Our findings are in agreement with those of Greenleaf and Reese (1980) and Lee et al. (2002), who reported no effects of bed-rest on the gain and magnitude of the sweating response after 14 days of bed-rest. In contrast to Lee et al. (2002), who noted a delay in the onset of the sweating response, we did not observe such a shift in the core temperature threshold for onset of sweating.

In contrast to previous studies, which conducted the exercise thermoregulatory tests in the supine position immediately following the cessation of bed-rest, our subjects conducted upright exercise on the second day of recovery. Upon assuming the upright position after prolonged exposure to bed-rest, the body fluid losses incurred during bed-rest are rapidly redressed. The most immediate responses are increments in plasma volume and extracellular volume (Fortney et al. 1991). We did not measure plasma osmolality in the present study, but based on the findings of Fortney et al. (1991) we postulate that the difference in the subjects' hydration status between the Post-bed-rest and Recovery trials was minimal. Assuming that the previously observed bed-rest-induced decrements in exercise sweating responses are due to reduced plasma volume, it is not surprising that no significant differences in the sweating response were observed in the present study.

#### Immersion temperature regulation

The greater rate of decrease of core temperature during the post-exercise immersion in 28°C water after bed-rest compared to recovery is attributed to the attenuated cold-induced vasoconstrictor response, reflected in  $\Delta T_{forearm-fingertip}$  (Fig. 3a), and an attenuated shivering response (Fig. 3b).

We postulate that most likely it is the factors associated with the observed decrease in peripheral vascular responsiveness that contributed to the attenuated vasoconstrictor response during immersion. Eiken and coworkers have demonstrated that repeated exposure of the peripheral vessels to elevated intravascular pressure decreases the distensibility (Eiken and Kolegard 2001), whereas withdrawal of the hydrostatic pressure gradients acting on the vessels, such as during prolonged bed rest, increases the distensibility of the peripheral veins, arteries and arterioles below heart level (Eiken et al. 2002).

The attenuated shivering response, reflected in the oxygen uptake, for identical levels of core and skin temperature may be a consequence of either a reduced thermogenic drive, a reduction in the intensity of shivering for the same thermogenic drive, or a combination of the two. For a given combination of core and skin temperatures, there is no evidence that the afferent neural-coded temperature information is affected by

prolonged bed-rest, which would favour the hypothesis that the observed alterations in shivering are due to bed-rest-induced changes in the efferent drive to the muscles for shivering and/or in the functional characteristics of the skeletal muscle. For a given efferent neural drive mediating shivering in skeletal muscle, the level of endogenous heat production will be proportional to the contraction intensity and the size of the muscle activated. Since motoneuron size and oxidative phosphorylation are unaffected by unloading the limbs (Edgerton and Roy 1996), the reduced heat production of a contracting (shivering) muscle is probably the result of the reduced mass and altered functional properties of the muscle (Kozlovskaya et al. 1981; Berg et al. 1991, 1997; Ferretti et al. 2001). Berg et al. (1997) reported that only two-thirds of the loss in muscle function following inactivity/unloading can be accounted for by the muscle atrophy, and suggests that reduced neural drive and/or changes in the force-generating capacity of the muscle also contribute to the reduced muscle function. Thus, it appears likely that this bed-rest-induced impairment in muscle function is also reflected in the attenuated shivering thermogenesis observed in the present study.

#### The effect of prior exercise on the immersion thermoregulatory responses

The similar exercise induced elevation in  $T_{re}$  in the Post-bed-rest and Recovery trials confirms the observations of Eiken and Mekjavic (2004) and Greenleaf and Reese (1980), that such elevations are dependant on the absolute rather than the relative work load. The absolute load was maintained at the same level in both trials, but due to the significant deconditioning incurred as a result of the bed-rest, the relative work load was greater in the post-bed-rest exercise. We cannot confirm the hypothesis that sweating and skin blood flow are proportional to relative work load, as there was no statistical difference in these responses between trials, but only a tendency towards higher values in the post-bed-rest values compared to those observed on recovery.

#### Behavioural temperature regulation

Defence of deep body temperature with behavioural responses may be compromised by bed-rest-induced changes in thermal sensitivity (Fortney et al. 1996). This was investigated in the present study by having subjects assign ratings of temperature perception and thermal comfort during exercise-induced heating and subsequent cooling in water. At any given  $T_{re}$  and  $T_{sk}$ , subjects felt significantly warmer ( $P < 0.05$ ) and less uncomfortable ( $P < 0.05$ ) after bed-rest than after recovery. Since subjective ratings of temperature and thermal comfort are a consequence of central processing of thermal afferent information, albeit by different central thermoregulatory foci, the observed alterations in thermal sensation may be attributed to either changes in the neural-coded

temperature information emanating from the core and peripheral temperature sensors, or to changes in the central processing of this information. Anecdotal comments of the subjects indicate that they perceived their thermal status transiently colder and were thermally more uncomfortable with the activation of shivering. It may be, that the post-bed-rest values of temperature perception and thermal comfort could, in part, be indicative of reduced shivering activity. Regardless, our observations provide further support that the previously observed down regulation of resting auditory canal temperature following 56 days of bed-rest (Winget et al. 1972) may partially also be attributed to changes in behavioural temperature regulation.

We, as others (Taylor et al. 1949; see also review by Fortney et al., 1996), have also noted subjects' commenting on the perception of cold feet towards the end of the bed-rest period. It is unlikely that this is due to ambient factors, since room temperature was maintained at 24°C during the entire bed-rest period, and subjects had adequate blankets. Infra-red thermograms taken at weekly intervals revealed that there was a significant decrease in skin temperature over the course of the 35-day bed-rest period, associated with a reduction of blood flow, which was attributed primarily to hypovolemia (Golja et al. 2002). Thus, the sensation of extremity cooling is not necessarily associated with an alteration in thermal sensory function (Fortney et al. 1996), but of extremity cooling.

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#### Conclusions

Our results reveal no significant effect of bed-rest on exercise thermoregulation for a given absolute work load. However, immersion in 28°C water induced a greater decrement in  $T_{re}$ , which is attributed primarily to the elevated skin blood flow, caused by the attenuation of the cold-induced vasoconstrictor response, and consequently greater heat loss from the skin, in conjunction with the reduced endogenous heat produced by shivering.

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