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CONTENTS

THERMAL "PORTRAIT" OF SPORTSMEN WITH DIFFERENT AEROBIC CAPACITY

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ABSTRACT

Nowadays thermography technique is widely used in clinical and diagnostic procedures. Thermal "portrait" fixed by infra-red thermotracer in rest conditions is characterized by mosaic temperature distribution on skin surface and large individual differences in this pattern. We obtained significant correlations between maximal and average temperature on sportsmen upper body part and important indexes of aerobic capacity – VO_{2max} and anaerobic threshold. We suggest mechanisms responsible for its formation and also propose hypothesis assuming possible role of brown adipose tissue influence on thermal "portrait" forming.

Key words: infrared thermography, VO_{2max}, anaerobic threshold

INTRODUCTION

Skin temperature is important marker of physiological state. Its evaluation has a real significance in situations concerned with adaptation to different environmental conditions and muscle activity

and also reflects heat production intensity which in turns depends on circulatory system recruiting level and sweating rate [8].

Though character of skin temperature distribution in regards to different physiological conditions has great research interest for a long time, technical difficulties did not permit wide using of respective methods. Recently multipoint contact thermometry was a primary method for such type of research but it gave rough estimated values of skin temperature and consequently only an approximate evaluation of organism thermal processes in the whole.

During last years novel infra-red thermovision analysis system devices differing from another one by high adequacy of analysis, possibility of covering more surface area and automatic calculation of average weighted skin temperature in fixed body zone have come into wide application. These techniques permit to use distant and noninvasive method which is absolutely safe and have not any contra-indications thus making it suitable for frequently repeating measurements [10]. Thermovision cameras obtain so called thermograms, original specific infra-red "portraits" of all body surface area or separate body segments. These "portraits" show temperature distribution corresponding to thermal state of appointed area.

In rest conditions thermoregulatory system provides temperature maintaining on relatively constant level. At the same time skin temperature of all body surface as on separate body segments can vary in a wide range – from 25.2 to 34 °C [1]. In elderly and senile persons it is observed skin temperature decrease caused by atherosclerosis and blood vessels infiltration and drop in blood flow related to capillary recruiting deficiency that results in lowering of thermoproduction level [7].

With use of contact-free infra-red thermo tracer it becomes possible to monitor skin temperature dynamics during muscle physical activity with graded load increase and during recovery period. Skin temperature dynamic and its recovery rate after unloading has shown sufficient depending on physical working capacity which some authors evaluate by maximal oxygen uptake level ($VO_{2\,max}$) [9].

Together with large individual differences thermography imaging method can reveal and visualize temperature distribution differences on skin surface area for each individual [4, 12, 13]. Forming mechanism of these differences relies on three basic factors: capillary net structure and its functional activity, sweat glands functioning and its density and metabolic activity of tissues underlying skin layer. In

combination with environmental conditions all these parameters provide to form a specific individual thermal "portrait" which analyzing in sportsmen of different specializations become main purpose of our research.

MATERIAL AND METHODS

Forty sportsmen mean age of 23.5±4.9, average weight 70±11.5 kg and average height of 174±7 cm took participation in experimental series. All participants passed through medical examination to confirm their functional suitability for experiment and also signed informal agreement. In accordance with protocol verified by Ethic Committee of All-Russian Research Institute of Physical Culture and Sports, smokers, post operated persons, reconvalescents, individuals with locomotor system disorders or any chronic diseases that could influence on thermoregulation processes were not examined.

All participants were fasted for 2 hours before experimental procedures and had no alcohol receiving 24 hours prior to the evaluation. During 15 minutes on initial phase of experiment each individual was located in isolated chamber for thermal adaptation in muscle rest conditions (air temperature was keeping up to 21–22°C, air humidity was 45%). This part of experiment was designed in so manner to initialize thermoregulation mechanisms activation. After 15 minutes of adaptation back surface thermograms was obtained by NEC TH 9100SL contact-free thermotracer. The camera was maintained at a distance of 3 m from the subject and at a height of 140 cm from the floor. Image Processor® Software was used to analyze thermograms. Thermotracer was calibrated every time before single thermograph making.

For a thermal state quantitative analysis all back surface (ABS) area was marked out on each thermogram (Figure 1). Minimal, maximal and average weighted temperatures were evaluated.

For maximal oxygen uptake level ($VO_{2\ max}$) evaluation test with graded load increase on treadmill (HP Cosmos) was performed. Initial track velocity was 7 km/h, then it had been increased on 0.1 km/h each 10s until the end of exercise performance. Gas analysis was realized with Oxycon Pro (Germany) which was calibrated every time before and after testing. Statistica 6.0 Software was used for statistical data analyzing.

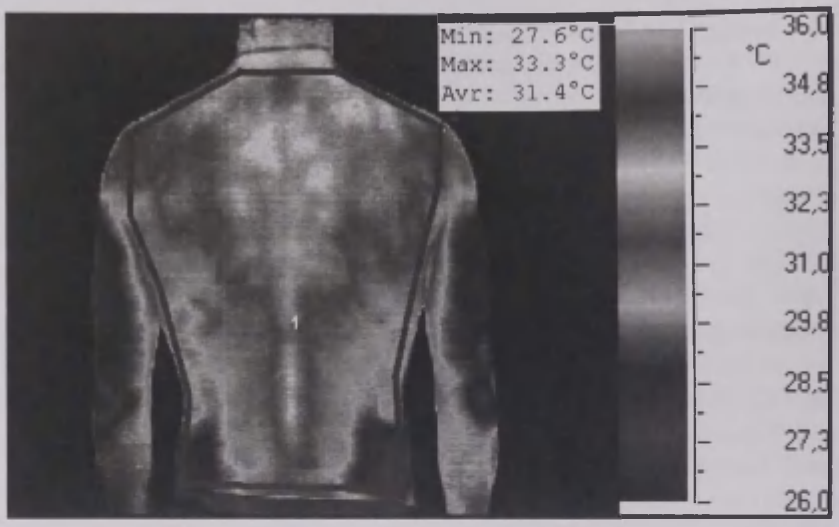

Figure 1. Back thermogram with marked zone for automatic analysis

RESULTS

ABS maximal temperature was 33.7±0.4 °C, average temperature of this zone was 31.6±0.5 °C and minimal was 28.9±1.25°C respectively. Average values of oxygen uptake on anaerobic threshold and VO_{2max} were 46.7±7.2 ml/min/kg and 65.5±8.7 ml/min/kg correspondingly. For analysis making all sportsmen were divided into 4 groups in relation to VO_{2max} values (intergroup difference was 10 ml/min/kg). Some single thermograms of sportsmen of each group are presented on Figure 2.

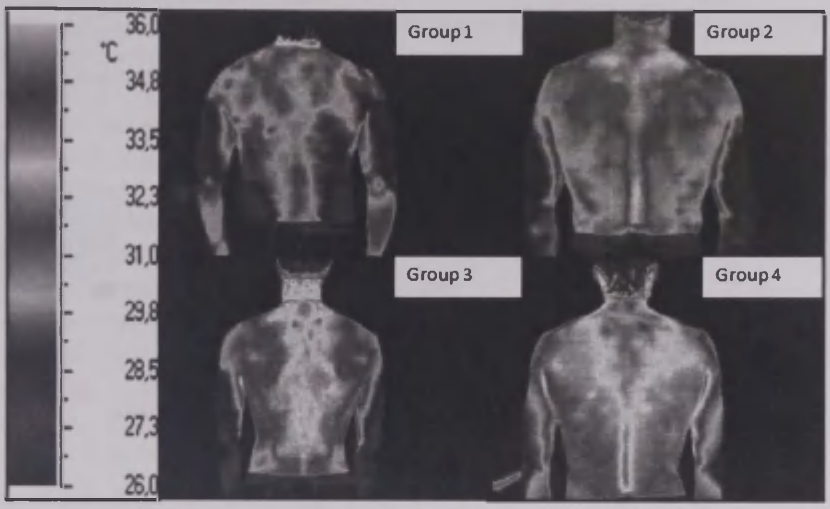

Figure 2. Back thermograms of sportsmen of different groups

We revealed that Group 1 had lowest values and also had lowest minimal, maximal and average ABS temperature comparing with other groups. In other groups increase in VO_{2max} level was associated with rise in ABS temperature (Table 1). At the same time pair groups differences were not significant, whereas differences between Groups 1 and 4 were statistically significant ($p<0.05$). Thus there was relation between ABS skin temperature and aerobic capacity. Sample correlation analysis revealed the significant correlation coefficients between VO_{2max} and ABS average temperature ($r=0.69$), VO_{2max} and ABS minimal temperature ($r=0.61$) and VO_{2max} and ABS maximal temperature ($r=0.51$) as seen on Figure 3. Furthermore we found correlation between oxygen uptake on anaerobic threshold and ABS average temperature ($r=0.63$).

Table 1. Group values of ABS temperature and VO_{2max}.

		Group 1 n=3	Group 2 n=6	Group 3 n=20	Group 4 n=11
VO_{2max}, ml/min/kg		40–50	50–60	60–70	70–90
ABS	Min °C	26.6±0.78	28.7±1.22	28.9±1.17	29.5±0.89
	Max °C	33±0.61	33.5±0.36	33.7±0.51	34±0.28
	Avr °C	30.5±0.5	31.5±0.34	31.7±0.43	32±0.37

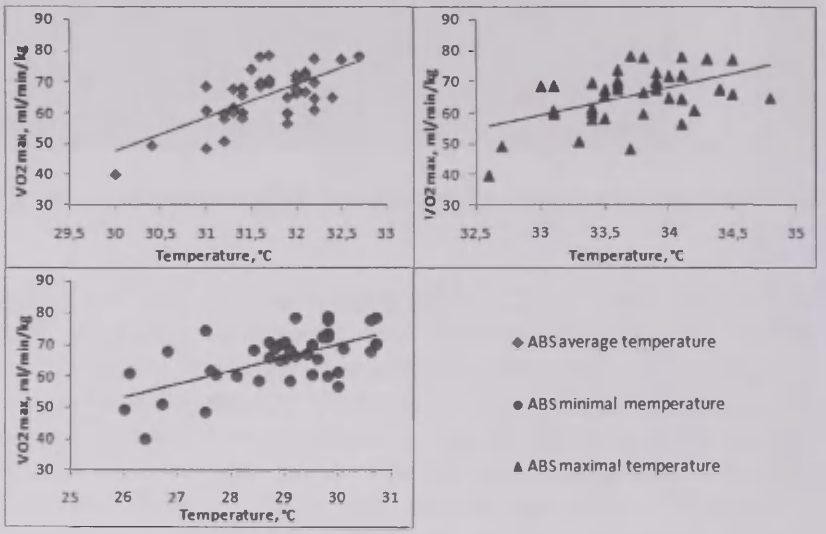

Figure 3. Correlation between VO_{2max} and ABS temperature

DISCUSSION

New options of modern infra-red thermography video technique allow seeing mosaic distribution of temperature on body skin surface of person located in conditions due to moderate activation of thermo-regulation processes (comfort humidity, temperature 5–7 °C below thermoneutral) during 15 minutes period. We confine ourselves with examination of back surface area only as it presents a homogeneous massive in respect to skin layer thickness. In spite of well pronounced

individual differences it is possible to mark out several zones on back surface that demonstrate increased or decreased temperature as compared with average weighted one in most cases. Almost all examinated persons show increased temperature in cervical region, in thoracic spine area and also in lumbar vertebral area seen as tight stripe shaped zone. On the contrary lateral back regions demonstrate low temperature values differed from most hot spots on skin surface by 7–8 °C. These results are in agreement with other researches using similar methods [7, 9].

Nevertheless main question is the cause of mosaic distribution of skin temperature. Only getting the answer we can approach to adequate explanation of obtained results and perhaps thermography imaging will hold its place among diagnostic procedures. Today however the situation in this context is not clear.

There are three processes that can determine local differences in skin regions due to heat dissipation which is essentially fixed by thermal imaging. First process is local blood flow that depends on skin capillaries density (anatomic factor) and vasoconstrictive muscles tonus (vascular tonus autonomic regulation factor). Second process is sweating intensity (sweat glands density and distribution) and its cholinergic activation by sympathetic system. Third process is metabolic activity of tissue lying directly under skin layer controlled by adrenergic stimulation pathways of autonomic nervous system. Our scheme implying seminude persons 15 minutes exposition in room with an ambient temperature of 22 °C (i.e. notably lower thermoneutral) should initialize sympathetic activation – a typical systematic reaction of thermoregulatory system on cooling. It might result in sweating rate decrease (and heat irradiation decrease as consequence), increase in skin vessels tonus (with the same consequence) and also rising metabolic activity of tissue that is under sympathetic control (and increase in heat irradiation respectively). Contradiction of these reactions does not permit to make unambiguous prognosis of final result in local skin temperature – will it decrease or increase. Correlation coefficients between skin temperature and parameters of aerobic capacity we obtained, not very high but statistically significant reflects with high probability these contradictionary tendencies in organism reactions to moderate short-time cooling. The fact of concordance of aerobic capacity level and such sympathetic dependent parameter as skin temperature undoubtedly presents great interest for discovering mechanisms that determine physical working capacity.

Early in our research on cosmonauts in conditions of long-term cosmic flight we found strong dependence of aerobic capacity on activity of autonomic nervous system sympathetic branch [11].

It is well known that one of the most metabolically active tissues of human organism is brown adipose tissue [2]. Its activity is under strong sympathetic control [3]. Recent research materials disprove early point of view that brown adipose tissue is inactive in adult people. It is proved that considerable part of adult population has active brown adipose tissue [5]. Its localization is differently presented by authors but more frequently mentioned regions are cervical and supraclavicular areas. Children brown adipose tissue has its main location in cervical and intrascapular zones that is similar with temperature distribution of some individuals in our experiments (see Figure 2, Group 4). Brown adipose tissue contributes to carbohydrate and lipid metabolism during intensive food intake promoting normalization of carbohydrates and lipids in blood. This why converting of white fat in brown to fight obesity is one of the aims of novel genetic engineering investigations [6]. New molecular genetic researches found adipocyte precursors of brown adipose to be much more closer by its characteristics to muscle precursors cells that to white adipose tissue precursors. In that aspect our data suggesting correlation between VO_{2max} and back surface temperature obtain another aspect. Even though it's not enough for concluding that sportsmen with high VO_{2max} values and aerobic capacity have significant amount of brown adipose tissue this proposition seems quite logic and in turns it gives new direction for future investigations.

CONCLUSIONS

Thermal "portrait" fixed by infra-red thermotracer in conditions of moderate activation of thermoregulation is characterized by mosaic skin temperature distribution on back surface and large individual differences in this pattern. We obtained significant correlations between maximal and average temperature on upper body part of non-clothed sportsmen located in room with normal ambient temperature and parameters of aerobic capacity – VO_{2max} and anaerobic threshold. For physiological explanation of such correlation we suggest mechanisms responsible for its formation and also propose hypothesis assuming possible brown adipose tissue influence on sportsmen

thermal "portrait" forming in moderate conditions out of thermo-neutral zone.

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THE EFFECT OF KNEE JOINT ANGLE ON THE COACTIVATION OF PREPUBERTAL BOYS AND ADULT MALES

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ABSTRACT

The purpose of this study was to investigate the influence of knee joint angle on the maximum moment and activation level of the knee extensors and flexors for untrained pre-pubertal boys (n=25; age 9.8±1.1) and adult males (n=25; age 29.6±5.0). Three maximal isometric voluntary knee extensions and flexions were performed at 3 different joint angles (5%, 50% and 95% of the maximal range of knee flexion), while the integrated averaged electromyographic (iaEMG) activity of the vastus medialis (VM), vastus lateralis (VL), and long head of biceps femoris (BF) muscles were recorded. The results indicated that absolute and relative torque was higher in adults compared to children. Agonist activity was not affected in both groups by joint angles. Antagonist activity was higher in extreme angles in both groups and higher in children in all selected joint angle. These findings suggest that the joint angles caused a deficit in neuromuscular performance of children and it could be attributed to their higher antagonist activity.

Key words: muscle length, electromyography, co-activation, pre-puberty, knee

INTRODUCTION

The influence of muscle length on the torque output has been widely studied *in vivo* and *in vitro* in the past, confirming torque output alteration when muscle length changes [36]. This torque alteration is referred as length/tension relationship and it is usually expressed as torque/joint angle (TJA) relationship. The TJA history was mainly attributed to the so called "sliding filament theory" [36], according to which an overlap or reduction of actin-myosin cross bridges is observed at short or long lengths, respectively. Relevant studies have also shown that TJA is also affected by biomechanical [34, 36] and neuronal [24, 34] factors, as well.

Regarding the neuronal mechanisms conflicting results have been reported for the agonist and antagonist activity. Muscle agonist activity may be higher [4, 23, 25, 27, 29, 45] or unaltered [10, 33, 48] at the extreme angles. Similar controversy exists for the antagonist activity. It has been reported that coactivation is higher at the extreme angles [12, 23, 25, 27, 30, 43] or it remains constant [4, 8, 16].

During the developmental period, skeletal muscles undergo structural, neural, metabolic and morphological changes [9]. Such changes result in a continuous strength increase due to the moment arm increase [34], and the muscle mass increment [38]. Regarding the neuronal factors prepubertal children exert their torque based on their feed forward system [42] and activate their motor unit in the same extend adults do, during plantar flexion [17, 18] and knee extension [34, 44]. Children also demonstrated longer, electromechanically delay and lower rate of force development [3, 13]. The results are conflicting for the antagonist activity during Maximal Isometric Voluntary Contraction (MIVC). Children compared to adults have higher coactivation during plantar flexion [17, 18] and elbow flexion [13] but no difference is observed during knee extension [34] and during maximal isokinetic knee contractions [6].

The effect of joint angle has not been extensively studied in children. Marginson & Eston [31] and Marginson et al. [32] reported that adults produced less relative knee extension torque(corrected to the maximum one) than children at flexed knee position higher than 80°,(0° is knee full extension) due to the more compliant muscle tendon unit that children have [26, 28]. O'Brien et al. [34] however did not observed such differences between adults and children studying in the TJA relationship in a range of motion between 50 and

90 deg. Besides, O'Brien et al., [34] reported that boys and adults did not have any difference, in the joint angle that maximal torque is produced and in the activity of the evaluated agonist and antagonist muscles across the joint. Nonetheless, according to our best knowledge there is no information about the differences in neuromuscular activity between children and adults at joint angles close to knee full extension or close to full flexion. This is an important issue if we consider that Anterior Cruiciate Ligament (ACL) loading occurs when knee is extended [1, 25] and that higher antagonist activity is expected at higher flexed position due to neural factors [27]. Furthermore, there is no information regarding the influence of joint angle in relative torque (corrected to body mass) if we consider that generally this is a conflicting issue. Depending on the applied normalisation method, in some cases equal values have been reported between age groups while in other, higher values for adults [47].

Based on the above, the purpose of this study was to investigate the differences in relative torque, agonist and antagonist activation between prepubertal boys and male adults and the effect of knee joint angle.

MATERIAL AND METHODS

Subjects

Twenty five prepubescent boys (age 9.8±1.1 years; height 144.1±7.2 cm; body mass 40.7±9.0 kg) and twenty five adult males (age 29.6±5.0 years; height 181.0±5.3 cm; body mass 83.5±8.6 kg) volunteered to participate in this study. Parental and subject informed consent was taken prior to the participation in the experiment. Prior to the test all subjects passed medical examination. None of them was systematically trained or had any injury or neuromuscular disease at the lower limbs. All children were examined by a medical doctor who classified them to the first or second maturation stage according to Tanner's criteria [46]. The screening procedure excluded subjects having body fat more than 25% of their body mass because this could bias the EMG recordings. The study was performed according to the principles of the Ethics Committee of Aristotle University of Thessaloniki.

Instrumentation

All MIVCs were performed on a Cybex Norm (Lumex Corporation, Ronkohoma, NY) dynamometer which was calibrated prior testing according to the procedures recommended by the manufacturer. The EMG recordings were captured with the Neuropack Four Mini device (Nihon Kohden Co.) which was connected with the Biopac, MP100 (Biopac Systems, Inc., Goleta). For anthropometric characteristics and body mass evaluation the following instruments were used: Height meter, Caliber for body fat mass.

Procedure

All subjects visited our laboratory two times, a week apart. The aim of the first visit was to inform and familiarize the participants with the dynamometry and testing procedures. During this session, subjects were at prone position and exerted submaximal and maximal knee flexions. Afterwards the subjects were familiarized at positions which responded to the 5%, 50%, and 95% of their maximal range of knee maximal flexion (Table 1). The maximal knee flexion was evaluated energetically. Three trials were performed and the average values were finally accepted.

The MIVC was recorded for further evaluation during the second visit. The trunk, waist and thigh of the right leg of the subjects were stabilized at prone position with Velcro straps. The rotation axis of the dynamometer was aligned carefully with the approximate center of rotation of the knee on the posterior aspect of the lateral femoral condyle. From this position the subjects performed MIVC at 5%, 50%, 95% of their maximal Range of Motion (MROM, 0° defined as the position of full knee extension).The selection of fixed joint angles would respond to different stretching output for each subject and for this reason percentages of the ROM were selected. Besides according to Maganaris et al. [30] flexibility affects joint/torque relationship.

Before the MIVC evaluation the participants performed a specific warming up 15–20 submaximal isometric contractions with gradually increasing intensity. Then, they performed maximal isometric extension and flexion lasting 5 s each, with verbal encouragement and visual feedback of the torque output. A visual marker on the screen indicating their previous maximum assisted them to try achieving better performance. This procedure was continued until the last three trials showed no further increase in torque provided that all of three of them did not differ more than 5% from each other. To avoid any

fatigue effect the interval between maximal trials was 3 minutes. The highest value was selected as the subject's MIVC. The lean body mass was evaluated according to Slaughter at al. [41] and torque was normalized to their body (BM) and lean body mass.

EMG recording

The EMG activity was differentially recorded using bipolar surface electrodes (Ag-AgCl) of 0.8 cm diameter and the inter-electrode distance was set at 1.2 cm. Before the electrode placement, the skin surface was shaved, abraded with sand paper and cleaned with alcohol wipes in order to reduce skin resistance below 5 kΩ. Skin resistance was measured with the built-in device of the Neuropack apparatus. The surface of the electrodes were covered with a conduction gel (Ten20) and fixed with adhesive tape on the skin. The electrode cables were fixed with tape as well. The electrode placement sites were identified exerting a MIVC from the seated position for vastus medialis (VM) and vastus lateralis (VL) and from prone position for the biceps femoris (BF). The electrode location for the VM was the distal portion of the muscle, above and medially from the superior border of the patella in the one third of the distance between epicondyle and greater trochanter. The electrodes were also placed on the VL laterally to the rectus femoris, on the bulk of the muscle, half-way between the lateral femoral epicondyle and greater trochanter. For the BF the electrodes were located over the long head of BF, half way on the line between the ischial tuberosity and head of the fibula. The ground electrode was positioned on the bony surface on the lateral epicondyle.

Torque exerted at the 5% and 95% of maximal Range of Motion was normalised to torque exerted at 50% of ROM.

Signal processing

The EMG signal was amplified (x1000), 10 Hz to 500 Hz bandpass filtered. The analog signals of the dynamometer (torque and angular position) and EMG device were digitized at sampling rate of 1 kHz through the integrated A/D 16bit card of the Biopac MP 100 Data Acquisition unit (Biopac Systems, Inc., Goleta, CA). The EMG signal was fully rectified, integrated and averaged (iaEMG). The iaEMG value of VM, VL, and BF was calculated 500 ms before and after the maximal torque. All data stored in a computer for further analysis by the Acknowledge software program (Biopac Systems Inc., CA).

The antagonist EMG activity of BF was expressed as percentage of the BF EMG recorded during maximal voluntary isometric flexion.

Statistical analysis

Standard statistical methods were used for the calculation of mean values and standard deviations (SD). The dependent variables for torque, EMG and co-activation, were analyzed with 2×3 mixed repeated measures ANOVA with age (prepubescents, adults) and joint angle (5%, 50%, 95%), as the independent variables. Post-hoc comparisons of the treatment means (Tukey's test) were used if appropriate. Interactions, main effects and mean differences were considered significant and reported as such when the level of probability reached or exceeded 0.05.

RESULTS

The highest peak value was observed during MVC of knee extensors in 50% for both age groups. The two-way interaction effect was also significant on knee extensor moment. There was a significant F-ratio for the Joint Angle ($F_{2.96}$=200.8; $p<0.001$) (50%>95%>5%) and Age ($F_{1\,48}$=392.2; $p<0.001$) (adult > prepubescent males) (Figure 1; Table 1).

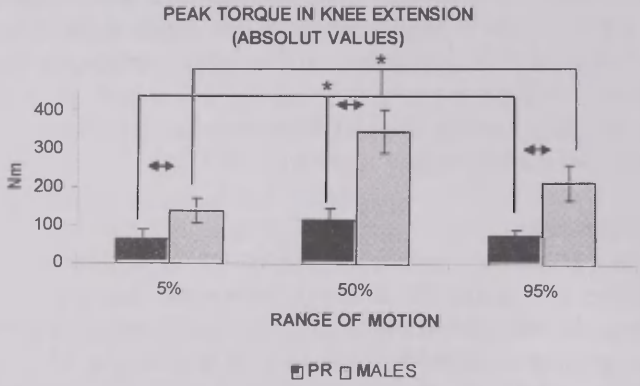

Figure 1. Peak torque values in knee extension (absolute values) of children and adults during MIVC. Horizontal arrows and asterisks indicate significant difference between the knee flexion angles and the age groups, respectively.

Table 1: Maximal Range of Motion and 5%, 50% and 95% of max ROM (in degrees) for the two age groups.
Mean (SD) values and post-hoc test comparison results of the factors Age and Angle for the knee extension torque in absolute and normalized values ($p<0.05$).
Mean (SD) values and post-hoc test comparison results of the factors Age and Angle for the EMG activity (in mV) of VM, VL and BF and antagonist activity of BF.

	Prepubescent (n=25)			**Adults (n=25)**		
Range of Motion (ROM) (degrees)	5%	50%	95%	5%	50%	95%
	6.41 (0.2)	61.6 (11.8)	121.79 (4.7)	6.2 (0.2)	60.4 (11.2)	119.3 (4.6)
Max ROM (100%)	128.2 (4.9)			125.6 (4.9)		
Peak torque	5%	50%	95%	5%	50%	95%
Knee extension (N·m)	62.5 (25.7)	112.4 ^{ab} (32.5)	74.6 (16.2)	138.1 † (32.6)	347.6 $^{\dagger ab}$ (57.4)	211.2 $^{\dagger c}$ (46.2)
Knee extension torque normalized to body mass ($N \cdot m \cdot kg^{-1}$)	1.5 (0.5)	2.8 ^{ab} (0.7)	1.9 (0.5)	1.7 (0.4)	4.2 $^{\dagger ab}$ (0.6)	2.5 $^{\dagger c}$ (0.5)
EMG of VM extension (mV)	1.7 (0.7)	1.6 (0.6)	1.5 (0.7)	2.3 † (0.8)	2.3 † (0.9)	2.1 † (1.0)
EMG of VL extension (mV)	1.7 (0.6)	1.6 (0.7)	1.5 (0.7)	2.9† (1.1)	2.8 $^{\dagger b}$ (1.0)	2.3 $^{\dagger c}$ (1.1)
EMG of BF flexion (mV)	1.9 (0.7)	1.7^{b} (0.6)	1.1^{c} (0.6)	3.0† (1.3)	2.3 $^{\dagger ab}$ (0.9)	1.4^{c} (0.6)
Co-activation BF	32.8 (11.0)	27.6^{ab} (11.0)	38.1 (12.5)	23.6† (13.4)	20.6$^{\dagger ab}$ (9.1)	35.3† (10.8)

† significant difference between the groups
^{a} significant difference between the 5% and 50% ROM
^{b} significant difference between the 50% and 95% ROM
^{c} significant difference between the 5% and 95% ROM

When torque was normalized to body mass (BM), adult males had greater values than prepubescent, ($p<0.05$). Between groups data are presented in Figure 2.

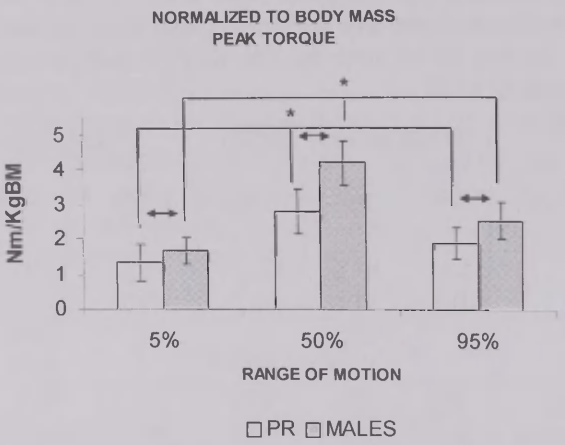

Figure 2. Peak torque values in knee extension (normalized to body mass) of children and adults during MIVC. Horizontal arrows indicate significant difference between the knee flexion angles.

Normalizing the torque to the respective values during the contraction at the midpoint of ROM (50%), data showed significant effects for the factor Age during extension ($F_{1,48}=13.2$; $p<0.001$).

The iaEMG of the VM and VL was similar at all angles for both age groups (Figure 3). For the antagonist normalized EMG of BF there was a significant F-ratio for Age ($F_{1,48}=9.0$; $p<0.05$) and Joint Angle ($F_{2,96}=111.6$; $p<0.01$) (Figure 4). Post-hoc Tukey's test indicated that the antagonist EMG recorded at 5% and 95% of ROM was significantly higher compared to the EMG recorded at the midpoint joint position for both groups (Figure 4: Table 1).

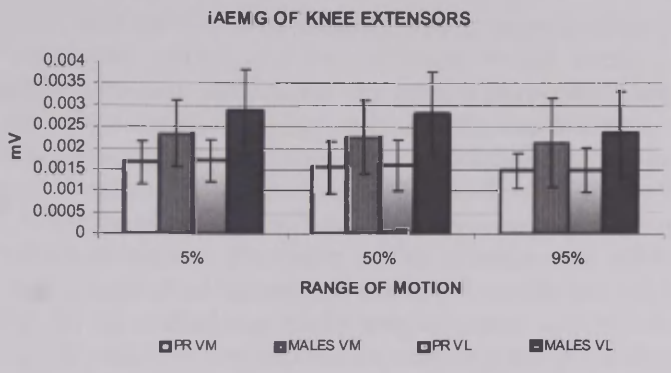

Figure 3. Agonist EMG activity of children and adults during MIVC for the vastus medialis (VM) and vastus lateralis (VL) during knee extension. Horizontal arrows and asterisks indicate significant difference between the knee flexion angles and the age groups, respectively.

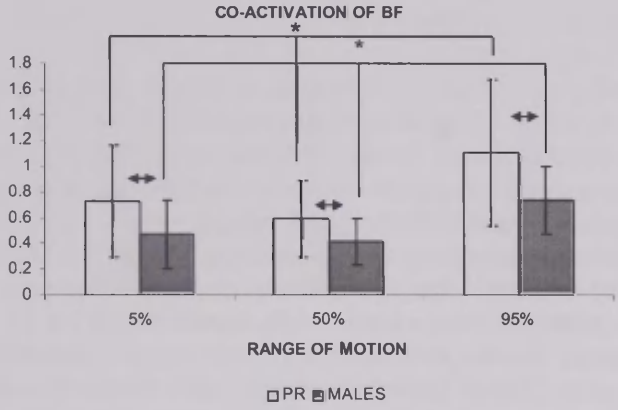

Figure 4. Antagonistic EMG activity of the biceps femoris (BF) during maximal knee flexion at different knee angles. The antagonistic EMG is normalized to the maximum EMG recorded when the respective muscle was acting as agonist at the respective knee joint angle. Horizontal arrows and asterisks indicate significant difference between the knee flexion angles and the age groups, respectively.

DISCUSSION

The main findings of the current study were that the absolute and relative torque was higher in adult males for all selected joint angles while when the torque was normalized to the torque exerted at 50% of MROM statistical differences were observed only at the 5% position. Agonist activity remained constant both in prepubescent boys and adult males irrespectively of the selected joint angles. Coactivation was higher in the two extreme angles in both age groups while prepubescent boys exerted higher values relatively to the adult men.

The obtained absolute torque was higher in adults compared to prepubescents in all tested angles as expected. When the torque at 5% and 95% of the ROM was normalized to the exerted torque at the midpoint position, significant differences between the age groups were observed only at the 5% position. The absence of significant differences at the position of 95% of ROM despite the higher decrease in adults could be supported by Marginson & Eston [31] and Marginson et al. [32] who showed that the relative torque decreased significantly more in adults than in children after 90 degrees of knee flexion.

Regarding the effect of joint angle our results showed that relative torque was higher in adults in all selected joint angles. Generally speaking the differences in relative torque output between adults and children is a conflicting point. Some researchers reported that torque differences between different age groups were eliminated when absolute strength measures were normalized to body parameters [35, 40]. On the contrary, it has also been reported that differences between ages still remained even after strength normalization [6, 13, 19, 20]. According to Tonson et al. [47] in some cases it depends on the applied normalization method, since relative force was higher in adults when torque was normalized to Anatomical Cross Sectional Areas (ACSA) and muscle volume as derived from anthropometric parameters. However, normalized torque was not different between age groups when it was expressed in respect to muscle volume as estimated by MRI. Taking into account the above we may comment the following. Firstly, Tonson et al. [47] comments might be valid only for the handgrip contraction if we consider that the same methods for relative torque evaluation give different result across different muscles and between different genders [13, 20]. Secondly, the more valid predictor for torque output is the ACSA and not the muscle

volume [5]. The latter is more valid for power normalization [5]. The above mentioned studies at previous works which normalized the absolute torque to the ACSA and reported higher values for adults compared to children [13, 20] support indirectly our findings.

The differences in relative torque between the age groups could be explained by potential differences in the extent of motor unit activation. However, it seems that this is not the case, since prepubertal boys and adults activate their knee extensor motor units in the same extent [34, 44]. Other arguments for causing the higher relative torque in adults are the differences in the moment arm which is lower in children [34] and the antagonist muscle activity, which, according to our results, is higher in children and this counteracts the agonist muscle activation which is not differentiated between prepubescent boys and adult men. Therefore, the moment arm and the antagonist activity differences between the selected age groups can explain the lower relative torque in children.

The relevant studies related to the antagonist activity in different joint angles are conflicting. In some cases no effect of joint angle is reported [4, 8, 16, 34] while in other cases a higher coactivation exists at the extreme knee ankle [12, 23, 25, 27, 43] and ankle [30] joint angles. Concerning the knee joint it was reported that the higher coactivation at shorter muscle length (near full extension), could be attributed the synergy of Anterior Crusiate Ligament (ACL) with BF muscle at these joint angles due to the strain on ACL increased [13, 23, 43]. Another reason is that higher knee joint instability occurs when quadriceps muscle contracts at this position both in isometric [25] and concentric [1] conditions. In the case of increased coactivation at longer muscle length, it has been argued that joint afferents involvement might be involved [26] nonetheless, there is no concrete explanation. Therefore this issue needs further investigation. Besides our result indicate that both children and adults have common strategy for antagonist activity at least for the selected task.

We found also, that antagonist activity was higher in all selected joint angles in children. Previous comparisons of children with adults in antagonist activity lead to conflicting results. Specifically, in some cases a higher antagonist activity in children was observed for complex movements [15]. Co-contraction in three age groups of children during treadmill locomotion whereas in other cases during plantar flexion [17, 18] and elbow flexion [13] MIVC co-contraction was higher in children. However, a similar study for the knee

extensors MIVC revealed no difference between age groups [34]. Regarding the effect of joint angle on antagonist activity in children and adults for the knee extensors, only one study [34] reported no differences in coactivation between age groups for a ROM between 50 and 90 degrees. This controversy to our results could be attributed to methodological differences for the evaluation of the antagonist activation. In the study of O'Brien et al. [34] the torque output of the antagonist muscles is estimated, as derived from the antagonist EMG activity, whereas in our study, the coactivation calculation remains strict to the EMG values of the antagonist muscle (normalized to the EMG activity of the same muscle when acting maximally as agonist). Furthermore the examined ROM is different between the two studies. The present study evaluated more extreme positions. Last but not least, the leg extension in our experiment was executed from prone and not seated position. This difference may influence the muscle length of the quadriceps and especially the rectus femoris, and consequently this may influence the activation level [37]. Besides, keeping in mind that antagonist activity is task depended [22] the task selected in our study is very unusual in everyday life and therefore children may have been less experienced in such tasks (learning factor). Furthermore, knee joint laxity is higher in children compared to adults [2] and this may results in a higher co-contraction as a protective mechanism.

Concerning the agonist EMG activity our findings indicate fairly constant values between the groups and between the angles. However, the existing literature relevant to adults shows some controversy in this issue. Specifically, it was reported that activity in men is higher at shorter muscle lengths [4, 25, 29] because the neuronal transmission is lower than in the other joint angles [24] and consequently, the central motor drive increases compensatory, by an increase in the frequency domain. There are also studies which report that men have higher activation at the angle in which higher torque is produced, based on the fact that higher recruitment occurs due to the higher level of the exerted torque. For the case where higher muscle activation was observed at the longer muscle length [45, 48] the basic explanation was the higher enhancement of muscle spindle activity [7]. However, in other cases agonist activity was kept constant throughout joint angles [10, 33, 48]. A possible explanation could be given based on the observations of Brondino et al. [11] who reported that muscle inhibition -possibly caused by Golgi tendon organ- was constant

throughout all tested joint angles. However, other factors which can explain the observed conflicts regarding muscle activation relative to joint angles, are the artifacts which were observed in EMG recording at different joint angles due to shift of muscle during contraction, [14] or the signal cancellation which occurs during surface EMG evaluations [21].

One limitation of this study was that only three different joint angles were evaluated. Possibly it could be useful in future studies to use more joint angles for evaluation.

These findings suggest that the joint angles caused a deficit in neuromuscular performance of children and it could be attributed to their higher antagonist activity.

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TEMPORAL RELATIONSHIP BETWEEN INTRINSIC MOTIVATIONS IN PHYSICAL EDUCATION AND IN A LEISURE-TIME CONTEXT

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ABSTRACT

This study examined the temporal relationships between intrinsic motivation in physical education and in leisure time context over two year period. The stability, stationary and cross-lagged effects of the relationship between these variables over the two-year period was tested. Participants, 94 students (37 boys and 57 girls) aged 14–16 years (M14.9±0.90) at the beginning of the study, completed measures of intrinsic motivation in both contexts. The model indicated to the existence of significant impact from intrinsic motivation in physical education on intrinsic motivation in a leisure-time context but not in vice verse. The results showed that the degree of stability in intrinsic motivation in physical education was higher than in leisure time context over two year period. Additionally, the existence of stationary of the relationship between these variables was followed on both time points. This study demonstrated that intrinsic motivation in physical education is not affected by the previous intrinsic motivation in leisure time context.

Key words: intrinsic motivation, physical education, leisure time, covariance structure analysis

INTRODUCTION

Throughout the past decades several models have been proposed to better understand the dynamic interplay among motivational constructs. For example, Vallerand [16] proposed a hierarchical model of self-determined motivation (i.e. regulation of behaviors by choice and pleasure) where motivation operates and interacts at various levels, including the global level [2], the life domains level [5] and the situational level [6]. Guay et al. [4] investigating the stability of global self-determined motivation and school-determined motivation with a 1-year interval found that global self-determined motivation was not more stable than self determined school motivation. Also the existence of significant small reciprocal effect between global self-determined motivation and school-determined motivation was followed. Losier & Vallerand [11] who investigated the temporal relationship between perceived competence and self – determined motivation over 5 months period found that perceived competence determined motivation rather than the reverse. Recently, the trans-contextual model, proposed by Hagger et al. [7] specified the processes by which motivation for physical activity in a physical education context is transferred into a leisure-time physical activity context. However, up to data the reciprocal relation between intrinsic motivation in school physical education and intrinsic motivation for exercise behavior in leisure time is not clear.

The purpose of the present study was to test whether the relation between self-determined motivation like intrinsic motivation in school physical education and intrinsic motivation in exercise behavior during leisure time is reciprocal or simply horizontal over the period of two years. It was initially hypothesized that the constructs of intrinsic motivation in school physical education and intrinsic motivation in exercise behavior during leisure time will achieve discriminant validity at both time points. It was also hypothesized that intrinsic motivation in school physical education and intrinsic motivation in exercise behavior during leisure time would exhibit a high degree of stability, and that the relationship between these two variables would be stationary at two time points.

METHODS AND PROCEDURES

Students completed questionnaires on two occasions over a two-year period. The first time the questionnaires were administered, the students were in 8th ($n = 42$), 9th ($n = 20$) and 10th ($n = 32$) grades aged 14–16 yrs ($M = 14.9$, SD = 0.90). The participants (37 boys and 57 girls) completed measures of the intrinsic motivation for school physical education and for exercise behavior in leisure time context on two occasions over a two-year period. On both occasions the one week interval between the measures of motivation was used to minimise the amount of error variance introduced into the data that could be attributed to the use of similar measures of intrinsic motivation in physical education and leisure-time contexts. A modified version of perceived locus of causality scale [15] was used to measure intrinsic motivation in physical education. Intrinsic motivation in a leisure-time context was measured by the scale from Behavioural Regulations in Exercise Questionnaire [12]. During the two-year period, students were taking physical education as a required course.

Data analysis

The data were analysed using the LISREL 8.58 structural equation modelling (SEM) programme. To test the causal nature of the relationships between intrinsic motivation in school physical education and intrinsic motivation in exercise behavior during leisure time, the hypothesized structural model was specified in which reciprocal cross-lagged effects between these variables across time were estimated.

In addition, to examine the stability of the intrinsic motivation in school physical education and intrinsic motivation in exercise behavior during leisure time over the two-year period, the model specified direct effects of both intrinsic motivation in school physical education and intrinsic motivation in exercise behavior during leisure time measured at Time 1 on themselves measured two years later (Time 2). Finally, to test the stationarity of the relationship between intrinsic motivation in school physical education and intrinsic motivation in exercise behavior during leisure time were set to correlate at both time points.

Goodness-of-fit of the model with the data was evaluated using multiple recommended indexes of good-fit: the Comparative Fit Index (CFI), the Non-Normed Fit Index (NNFI), and the Standardized Root

Mean Squared Residuals (SRMSR). Cut-off values of 0.95 or above for the CFI and NNFI indicated acceptable models. Values of 0.08 or less for the SRMSR was deemed satisfactory for well-fitting model [10].

RESULTS

Preliminary analyses

Distributional properties of the responses to the all items were examined. A skewness value greater than one indicated that not all variables were normally distributed. Therefore, for further analyses PRELIS 2.51 provided the polychromic correlations, and its asymptotic covariance matrix. To fit the confirmatory factor models maximum likelihood method based on asymptotic covariance matrix was used, because this is suitable for ordinal data and standard errors. Descriptive statistics for the observed variables are presented in Table 1. The reliability coefficients of intrinsic motivations for different context in Time I and Time II were on acceptable level [13].

Table 1. Descriptive statistics of the observed study variables.

	Time I			Time II		
	Mean	SD	α	Mean	SD	α
Intrinsic motivation in PE	3.00	0.70	0.88	2.37	0.91	0.91
Intrinsic motivation in LT	5.15	1,34	0.86	5.19	1.39	0.92

Note. PE – physical education context; LT – leisure-time context.
α = cronbach alpha

Prior to testing the main hypotheses, to support the fit of the measures used in this study, a measurement CFA models that assumed discriminant validity were conducted and compared with a congeneric CFA models that did not assume discriminant validity. Goodness of fit indices for the series of congeneric and discriminant validity models at both time points are given in Table 2. Each of the discriminant validity models were superior in fit to the congeneric models at both time points. These analyses support the discriminant validity of two differentiated measures of intrinsic motivation in school physical

education and intrinsic motivation in exercise behavior during leisure time as hypothesised.

Main analyses

The main idea of the structural equation model was to test the causal nature of the relationships between intrinsic motivation in school physical education and intrinsic motivation in exercise behavior during leisure. The longitudinal model is presented in Figure 1. The goodness of fit statistics are reported in Table 2 (see Cross-lag model). Focusing on Time 1, it can be seen that intrinsic motivation in physical education and intrinsic motivation in a leisure-time context have strong relationship whereas the relationship between these two variables at Time 2 is not so strong. Focusing on the overall time-lagged model, intrinsic motivation in physical education and intrinsic motivation in a leisure-time context demonstrate autoregression over time. This tests the extent to which the distribution of the variable at Time 1, for example intrinsic motivation in physical education, overlaps with the distribution of that variable measured at Time 2. The extent to which they do not overlap provides confirmation that change has occurred in the variable over time and the standardized coefficient reflects the extent of this change. The results of the model demonstrated high degree of stability in intrinsic motivation in physical education from Time 1 to Time 2 (path coefficient = 0.59, with 95 percent confidence intervals (CI_{95}) = 0.37 to 0.81, $p<0.05$). In respect of intrinsic motivation in a leisure-time context students did not demonstrate as high degree of stability over time (path coefficient = 0.28, CI_{95} = 0.02 to 0.53, $p<0.05$). Cross-lagged relationships indicated to the existence of significant path from intrinsic motivation in physical education to intrinsic motivation in a leisure-time context but not in vice verse. Consequently, intrinsic motivation in physical education is not affected by the previous intrinsic motivation in leisure time context.

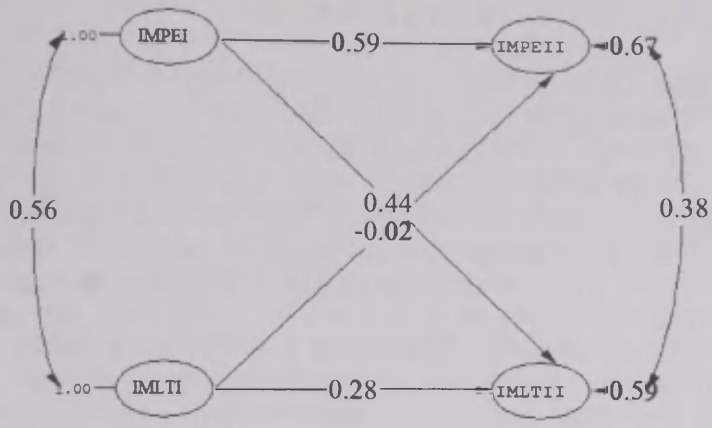

Figure 1. Cross-lagged model of intrinsic motivation in physical education and in leisure time context.

Notes: IMPEI – intrinsic motivation in PE at Time I; IMPLTI – intrinsic motivation in a leisure-time context at Time I; IMPEII – intrinsic motivation in PE at Time II; IMPLTII – intrinsic motivation in a leisure-time context at Time II
All paths, except the path from IMLTII to IMPEII are significant at $P<0.01$

Table 2. Goodess fit statistics for congeneric and discriminant validity confirmatory factor analytic models and cross-lag model.

	χ^2	d.f.	Models	RMSEA	CI_{90}RMSEA	*NNFI*
Congeneric model. Time I	141.67	20	0.84	0.257	0.220–0.300	0.78
Discriminant model Time I	34.91	19	0.98	0.095	0.042–0.140	0.97
Congeneric model. Time II	123.69	20	0.91	0.237	0.220–0.280	0.88
Discriminant model Time II	12.63	19	1.00	0.001	0.051–0.061	1.00
Cross-lag model	104.13	98	1.00	0.026	0.000–0.062	0.96

DISCUSSION

The main purpose of the present study was to test the causal nature of the relationships between intrinsic motivation in physical education and intrinsic motivation in leisure time context. We assumed that there are reciprocal cross-lagged effects between intrinsic motivation in PE context and intrinsic motivation in leisure time context and that both constructs will demonstrate a high degree of stability and stationary relationships over the two-year period. The present findings have important implications for at least two key issues. First, they suggest how intrinsic motivation at different contexts may influence each other. Secondly, they inform us about the stability of intrinsic motivation over time. Usually, the shorter the time, the stronger the relationship. However, in this study the stability of intrinsic motivation for both contexts was comparatively high over two year period. This result is consistent with findings reported by Gottfried et al [3]. The authors investigated the stability of intrinsic motivation in a longitudinal study of students from the middle through high school years and found that with advancement in age stability of intrinsic motivation even increased.

The cross-lagged model only partly supported the hypothesis about reciprocal effect between intrinsic motivation in physical education and in leisure time context because an unidirectional effect was apparent. Specifically, the path coefficient from intrinsic motivation in physical education (IMPEI) to intrinsic motivation in a leisure-time context (IMPLTII) was significant but not in vice verse (see Figure 1). This result is in some extent consistent with several previous studies [7, 8, 9] where the one-way effect from self-determined motivation in physical education on self-determined motivation in leisure time context were highlighted. The previous studies have documented the existence of the reciprocal effects between motivation at global level and at the contextual level [4, 17] and also between motivation at the contextual level and motivation at the situational level [1] but not between the same contextual levels. In our study intrinsic motivation in physical education and in leisure time context were observed as two different contexts on the same contextual level. The results of this study showed that intrinsic motivation in physical education has effect on intrinsic motivation in leisure time context even over two year period, but not in vice verse. Further, the relationships between

intrinsic motivation in physical education and intrinsic motivation in leisure time context weakened with advancement in age.

In terms of practical recommendation based on current results, it is important that teachers in promotion the motivation for leisure time physical activity first of all turn attention on intrinsic motivation in physical education setting, which in long perspective, has also impact on motivation in leisure time context.

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SUBJECTIVE AND OBJECTIVE ASSESSMENT OF NEUROMUSCULAR FATIGUE IN FEMALE PAINTERS

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ABSTRACT

The aim of this study was to evaluate subjectively and objectively neuromuscular fatigue in female painters before and after a working day. The subjects (n=11) were female painters aged 22–60 years. The subjects completed a questionnaire and gave a subjective evaluation on muscle fatigue sensation in hands, trunk, back and lower limbs according to Borg's Category Ratio (CR-10) scale. Thereafter they performed 3-minute test of painting a wall, in the course of which the electromyographical (EMG) power spectral median frequency (MF) slope for biceps brachii, trapezius, deltoid and infraspinatus muscles was measured. The results indicated a significant change in the subjective muscle fatigue sensation in hands by 40%, lower limbs by 54% and trunk by 57% after the working day, compared to the beginning of the working day. EMG power spectral MF slope of the measured muscles did not differ significantly during the 3-minute wall coloring test before and after working day. It was concluded that subjective muscle fatigue sensation in hands, lower limbs and trunk was higher after the working day whereas it was less pronounced in the back. Muscle fatigue evaluated objectively by MF slope of EMG power spectrum from biceps brachii, trepezius, deltoid and infra-spinatus muscles was not evident during the wall coloring test before and after the working day.

Key words: subjective, objective, muscle fatigue, electromyography

INTRODUCTION

The work-induced complaints of upper limbs can be described as disorders that involve neck, shoulders, arms, elbows, wrists, hands and fingers. They are caused by repetitive movements of fingers, hands or arms, including pushing, pulling, drawing, reaching, turning, raising, gripping or hitting. Most of all, this concerns professions such as painter, decorator, riveter, pneumatic tools operator and user of desk-top computer [4]. Salem et al. [7] measured the conformity of profession and the musculoskeletal diseases amongst 147 construction workers by a questionnaire. It was found that four factors connected with work (the working environment, mental work, performance and contentment) were closely related with the musculoskeletal symptoms, musculature and stress.

Garg et al. [3] studied shoulder girdle muscle strength of one hand in women when working with hands elevated above the head. It was found that women, especially in those professions that require working with hands elevated above the head, have little strength in their shoulder muscles. Chow and Dickerson [2] studied shoulder strength of females while sitting and standing as a function of hand location and force direction. It was found that there is a significant decrease in shoulder strength of females compared to males. Direction has the greatest affect on shoulder strength when working at or above-shoulder level. The optimal position that maximizes shoulder strength is vertically downwards.

The aim of this study was to evaluate subjectively and objectively neuromuscular fatigue in female painters before and after a working day. Measurements were carried out at the place of work at the beginning of the working day and after it.

MATERIAL AND METHODS

Subjects

Eleven females working as painters with (mean ±SD) age of 43.4±12.3 years participated in this study. The height, body mass and body mass index of the subjects were 163.5±9.1 cm, 78.3±16.2 kg and 29.3±5.4 kg/m^2, respectively, and their length of employment as painter was 19.5±13.9 years. The subjects were randomly selected and participated in the research voluntarily. The questionnaires and the measurements were completed in May and June, 2008. Larger facilities were chosen as the site of the measurements. Nine subjects were surveyed at the 1st stage of construction at the Tartu University Maarjamõisa centre of medical facilities and two subjects at the Tasku fashion and entertainment centre in downtown Tartu. The subjects were familiarized with the essence and the aims of the survey.

Data collection

The measurements were conducted at the beginning and at the end of the working day at the site where the workers were employed. So the subjects did not have to leave the site and the working rhythm was disturbed as little as possible, thus yielding more reliable results. The height and body mass of the subjects were measured at the site with metal anthropometer and electronic scales, respectively. The body mass index (kg/m^2) of the subjects was also calculated. The questions in the questionnaire were in Estonian and Russian. In the course of the research, subjects completed the questionnaire first. Subjective muscle fatigue sensation in hands, trunk, back and lower limbs was estimated with a psychophysical rating scale (Borg's CR-10 Scale). The scale included numbers from 0 to 10. Perceived exertion was estimated in the following way: 0–2 weak, 3–4 moderate, 5–7 strong, 8–10 extremely strong fatigue. Thereafter, a 3-minute test of painting the wall (Figure 1) was conducted.

Figure 1. Performing the dosed wall coloring test.

Muscle fatigue was objectively estimated by electromyographic (EMG) activity registered from biceps brachii, trapezius, deltoid and infraspinatus muscles using 8-channel electromyograph ME 6000 (Mega Electronics, Finland). The data gained were processed with the computer application MegaWin (2007). EMG power spectrum median frequency (MF) slope (%/kg·min) was calculated by the formula:

$$MF_{slope} = \frac{(MF_b - MF_a) \cdot t}{MF_b \cdot P \cdot 60} \cdot 100,$$

whereas MF_b is a EMG power spectrum median frequency at the beginning of the working day, MF_a is a median frequency after the working day, t is a test time (3-minutes) and P is the weight of the extension pole (3.2 kg).

Statistical analysis

When processing the data, the usual methods were applied for calculating the mean and the standard deviation (±SD). The significance of the changes for the group of subjects at the beginning of the working day and after it has been analyzed by using the pairwise t-test. The differences of the means of the group, as well as the significance of the changes for the group of subjects at the beginning of the working day and after, were evaluated on the basis of the Student t-test, $p<0.05$ was chosen as the statistically significant level.

RESULTS

The results indicated a significant subjective muscle fatigue sensation evaluated according to the Borg (CR-10) scale in hands ($p<0.05$), lower limbs ($p<0.01$) and trunk ($p<0.05$) before and after working day (Figure 2). At the end of the working day, the estimation of subjective muscle fatigue sensation increased by 40% for hands, by 30% for back, by 57% for trunk and by 54% for lower limbs as compared to the beginning of the working day.

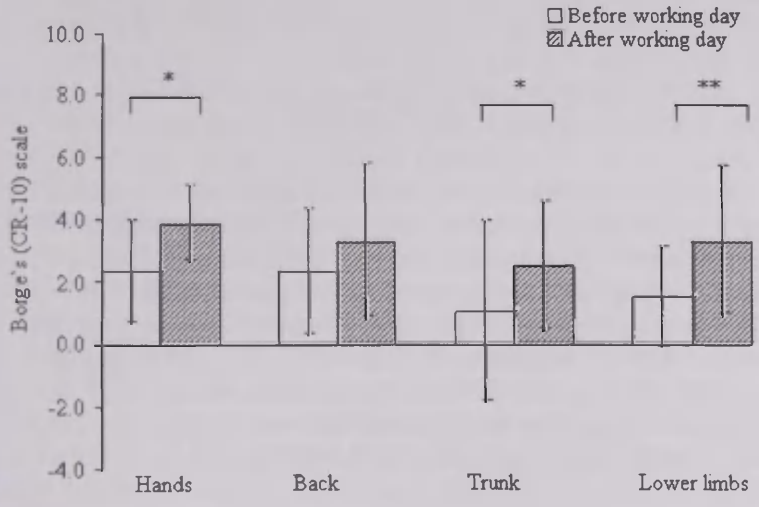

Figure 2. Subjective muscle fatigue sensation, estimated with a Borg's Category Ratio (CR-10) scale at the beginning of the working day and after it (mean ± SD); * $p<0.05$; ** $p<0.01$.

EMG power spectrum median frequency (MF) slope (Figure 3) of the measured muscle groups during wall coloring test did not differ significantly ($p>0.05$) at the beginning and after the working day.

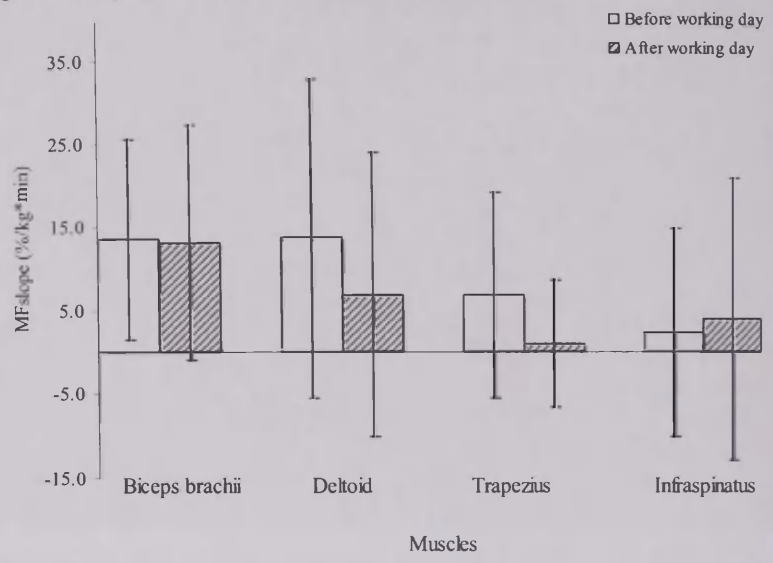

Figure 3. EMG power spectrum median frequency (MF) slope at the beginning of the working day and after it (mean ± SD).

DISCUSSION

On the basis of the Borg's Category Ratio (CR-10) scale [1], the female workers experienced subjectively muscle fatigue sensation after the working day more in hands, lower limbs, trunk and less in the back. A change in the subjective muscle fatigue sensation of hands, lower limbs and trunk before and after work was evident and this result deserves attention. It is known that physical stress and musculoskeletal discomfort when working can be alleviated and prevented by selecting the right tool that reduces the physical stress in the worker's fingers and hands to minimum, and he or she needs to use less energy for working. A correctly selected tool also reduces jolting, repulse, and vibration [6].

During the 3-minute wall coloring test, EMG power spectral activity MF slope did not change significantly but there was objec-

tively estimated muscle fatigue when comparing the beginning of the working day and the end of the working day. This can be related to the fact that at the beginning of the working day, the muscles have not yet reached their working capacity. The MF slope of the EMG power spectrum of the observed group revealed that in case biceps brachii, deltoid and trapezius muscles, this indicator was moderately lower ($p>0.05$) at the end of the working day. But in case of infraspinatus muscles MF slope it was moderately higher ($p>0.05$) at the beginning of the working day than it was at the end of the working day. This fact indicates that female painters tend to be more overloaded in the hands and shoulder region and less in the back.

The subjective muscle fatigue sensation of lower limbs may be due to the fact that painters have to stand throughout the working day mostly on concrete floor, which lacks the amortization that would reduce the jolting. Comfortable working shoes of good quality are of great help for reducing such overload in case of workers (including painters), who have to work standing all day long. A pair of shoes that does not suit one's foot can cause problems enduring for years [5].

The study revealed that painters were using different working styles, whereas the working tool was the same for everyone and no-one customized it for herself. It is also important to emphasize that 82% of the workers had not been instructed in terms of ergonomics.

Proceeding from the data gained in the course of the research, that the painters had mostly the shoulder girdle and hands overload, it is recommended that they perform stretching exercises before and during the working day. A worker should customize the tools proceeding from his/her own anthropometrical measures and use suitable means of protection. This requires the corresponding instructive materials and instructing the workers by a trained specialist. In case of physical work, it is advisable to make short breaks (5...10 minutes) every hour to avoid the problems caused by overload. Similarly important are the consumption of the necessary volume of liquids and following the balanced diet, since the current research and the previous ones have proven that in women, the neck and shoulder region are considerably burdened in case of physical work, indicating substantial expense of energy.

In conclusion, this study indicated that subjective muscle fatigue sensation in female painters was higher after the working day in hands, lower limbs and trunk, less pronounced in the back. Muscle fatigue, evaluated objectively by EMG power spectrum MF slope

from biceps brachii, trapezius, deltoid and infraspinatus muscles was not evident during 3-minute wall coloring test before and after the working day.

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PERFORMANCE INDICES OF TWO DIFFERENT REPEATED SPRINT TESTS PROTOCOLS IN OVERWEIGHT CHILDREN

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ABSTRACT

We determined the relationship between aerobic fitness and a short and long repeated sprint test (RST) in pre pubertal overweight children (10.5±1.5 yrs). Aerobic fitness was evaluated by the 20m shuttle run. Two RST protocols with identical total running distance were performed to determine anaerobic capacities at random order (12×20 m run departing every 20s and 6×40m run departing every 40s). Performance decrement (PD) and total sprint time (TS) were significantly higher in the 12×20 m compared to the 6×40 m protocol. Significant negative correlations were found between the aerobic fitness and TS (r= –0.767) and the fastest sprint time (r= –0.738) of the 12×20 m protocol. Similarly, significant negative correlations were found between the aerobic fitness and TS (r= –0.803) and the fastest sprint time (r= –0.787) of the 6×40 m protocol. There were no significant correlations between PD in both RST's and aerobic fitness. Performance of high number of short repetitions with very short recovery time is more difficult for overweight children than fewer longer repetitions with longer recovery time. Aerobic fitness plays an important role in intense intermittent activity, but not in PD from intermittent activity in obese children.

Key words: aerobic, anaerobic fitness, childhood obesity, repeated sprint test

INTRODUCTION

Children usually engage in spontaneous short exercise bursts separated by brief rest periods [2]. The ability of children to sustain intensity during repeated sprints was previously examined [24, 25, 33] using a wide range of age groups (9–17 yrs.) and different protocols of a repeated sprint test (RST). Compared to adults, small decrease in running performance was found in children [10]. Differences were significantly greater when the recovery intervals were short (15 sec) as opposed to long (180 sec). In addition, prepubertal males (9.6±0.7 yrs.) needed less recovery time to sustain peak power output compared to adolescent males (15.0±0.7 yrs) or young adults (20.4±0.8 yrs.) during repeated cycling sprints [24]. Consistent with that, pre-pubertal children repeated their initial performance faster following high-intensity exercise compared to young adults [17, 26].

Aerobic fitness was found previously as a prerequisite for anaerobic performance during repeated sprints [30]. Despite that, correlation analyses between VO_2 max and performance indices of RST were found inconsistent, and only few studies reported significant correlations between the two tests [e.g., 10, 20]. These relationships are especially relevant to children, due to their characteristic intermittent activity patterns. Testing the relationship between aerobic fitness and RST performance indices is even more challenging in overweight children. This group is particularly important due to the increased prevalence of childhood obesity in Westernized societies [27], and since both aerobic and anaerobic capacities are reduced in obese children [11, 19, 31]. Physical activity patterns of obese children are also characterized by brief exercise bouts, performed at different intensities and separated by different rest intervals [9, 21]. Thus, assessment of RST indices and their relationship to aerobic fitness in this population is important. Surprisingly, to the best of our knowledge, these relationships were not studied in obese children.

There are different protocols of RSTs; some use short sprint intervals, while others use long sprint intervals. The aim of the present study was to compare between short (i.e., 12×20 m), and long (i.e., 6×40 m) RST protocols, and to determined the relationship between the short and the long RST and aerobic fitness (measured by the 20m shuttle run test) in pre- and early-pubertal overweight children. Since patterns of physical activity among overweight children are usually characterized by short, rather than long, activity intervals, we

hypothesized that the performance decrement will be lower in the short compared to the long RST protocol, and that the shorter RST protocol will better correlate with aerobic fitness.

MATERIAL AND METHODS

Fourteen children (males=6, females=8; 10.5±1.5 yrs.) volunteered to participated in the study. All children participated in a weight reduction program in the Child Health and Sport Center at the Pediatric Department of Meir Medical Center. The study was approved by the Institution's ethical committee. All the children were assessed for obesity status and Tanner stage [18]. The testing procedure was explained to the children and to their parents, and a written informed consent was obtained from both.

Procedure

All participants performed three tests, separated by a week from each other, in random order. The three tests were an aerobic power test, a short interval RST and a long interval RST. Before each test, the children participated in a special habituation session.

Performance tests

Aerobic Power Test – Twenty-Meter Shuttle Run Test

The 20-meter shuttle run test is a field test that has been shown to be a reliable and valid indicator [28] of aerobic power in various populations [22]. The main reason for the use of this test in the present study to evaluate aerobic fitness was its back and forward run which characterizes children's voluntary activity patterns. It also eliminates the need to use laboratory equipment such as a motor driven treadmill and a face mask, which are unfamiliar and uncomfortable to children and especially to obese children. The test consists of shuttle running at increasing speeds between two markers placed 20 m apart. A portable compact disc (Sony CFD-V7) dictated the pace of the test by emitting tones at appropriate intervals. The children were required to be at one end of the 20 m course at the signal. A starting speed of 8.5 km/hour was maintained for one minute, and thereafter the speed was increased every minute by 0.5 km/hour. The test was terminated when the child withdrew voluntarily from the exercise, or failed to arrive within 3 meters of the end line on two consecutive tones. The aerobic fitness of

each participant was calculated as the total distance achieved during the test.

Repeated sprint tests

Two protocols of the RST were performed by the participants. Each protocol included a series of maximal runs with short rest periods between runs. The two protocols consisted of the following:

1. A short interval RST – Twelve X 20m runs starting every 20s.
2. A long interval RST – Six X 40m runs starting every 40s.

A 20m and a 40 m all-out sprint were performed following the warm-up of the 12×20 m and the 6×40 m protocols, respectively, by each participant. The time for each sprint was used as the criterion score for the subsequent RST. In the first sprint of each RST, participants were required to achieve at least 95% of their criterion score. If 95% of the criterion score was not achieved, the participant was required to start the RST again. None of the participants was required to restart the RST due to a slow initial sprint.

A photoelectric cell timing system (Alge-Timing Electronic, Vienna, Austria) linked to a digital chronoscope was used to record each sprint and rest interval time with an accuracy of 0.001s. During the recovery period between sprints, participants tapered down from the sprint they had just completed and slowly walked back to the next starting point. Two sets of timing gates were used, working in opposite directions, to allow participants to start the next run from the end-point of the preceding sprint, thus eliminating the need to hurry back to the same starting point. A standing start, with the front foot placed 30 cm behind the timing lights, was used for all sprints. Timing was initiated when the participants broke the light beam. An experimenter was placed at each end of the track to give strong verbal encouragement to each participant at each sprint. Participants were instructed prior to the test to produce maximal effort for each sprint and to avoid pacing themselves.

The three measures of each RST (12×20 m and 6×40 m) were the fastest 20 m or 40 m sprint time (FS), the total sprint time (TS) of the 12 or 6 sprints, and the performance decrement (PD) during each test. TS was calculated as the sum of all sprints times of each test. PD was used as an indication of fatigue and was calculated by dividing the sum of the sprinting times for each of the 6 or 12 sprints by the best possible total score multiplied by 100 [13]. The best possible total score was calculated as the fastest 40m or 20m sprint time multiplied

by 6 or 12, respectively. The test-retest reliability of the RST is 0.942 for total running time, and 0.75 for performance decrement [13].

Heart rate was measured using a Polar heart rate monitor (Polar Accurex Plus, Polar Electro, Woodbury, NY) immediately after completion of each run in both RSTs. Rate of perceived exertion (RPE) was determined using the modified Borg scale [8] at the end of each RST.

Statistical analyses

Paired t-test was used for comparing differences (in fastest and total sprint time, performance decrement, heart rate, RPE, etc.) between the two different RST protocols. Pearson correlations were computed between the calculated distance during the shuttle run aerobic test and performance indices of the two different RSTs. Data are presented as mean ±SD. Significance level was set at $p<0.05$.

RESULTS

Anthropometric characteristics of the study participants and the results of the 20 m shuttle run aerobic test are provided in Table 1.

Table 1. Anthropometric measures and total distance (Mean ± SD) during the 20m shuttle run of the study participants (N=14).

Parameters	Mean±SD
Age (yrs)	10.5±1.5
Pubertal Stage (Tanner)	1.2±0.4
Body Height (m)	143.5±7.9
Body Weight (kg)	52.5±10.0
BMI (kg/m^2)	25.1±4.7
BMI percentile (%)	96.4±1.9
Distance-20m shuttle run (m)	468.6±107.4

Performance indices of the two different RST protocols are given in Table 2.

Table 2. Performances indices (Mean ± SD) and protocol characteristics of the two RSTs (N=14).

Indices	6×40m	12×20m
Fastest Sprint (sec)	9.01±1.35	4.71±0.65*
Total Sprint Time (sec)	56.04±8.71	60.30±9.05*
Performance Decrement (%)	3.62±1.62	6.56±3.62*
Total Run Distance (m)	240	240
Total Rest Time (sec)	200	220*
Total Practice Time (sec)	256.0±8.7	280.3±9.1*
Maximal Heart Rate (beats/min)	186.4±11.1	192.2±8.3
RPE Score	3.6±1.3	5.1±1.5*

* $p<0.05$ for between-test differences

The performance decrement, total sprint time, total rest time, and total practice time were significantly higher in the 12×20 m protocol than in the 6×40 m protocol. The fastest sprint time was significantly lower in the 12×20 m protocol than in the 6×40 m protocol. RPE scores were significantly higher in the 12×20 m protocol than in the 6×40 m protocol.

The correlations between the 20 m shuttle run aerobic test and performance indices of the two RSTs are summarized in Table 3 and Figure 1.

Table 3. Relationships between 20m distance shuttle run and performance indices in the two RSTs. Data presented as r values.

RST Protocol	Performance Indices	20m Shuttle Run
6 × 40m RST	Fastest Sprint Time (sec)	–0.787*
	Total Sprint Time (sec)	–0.803*
	Performance Decrement (%)	–0.344
12 × 20m	Fastest Sprint Time (sec)	–0.738*
	Total Sprint Time (sec)	–0.767*
	Performance Decrement (%)	–0.326

* Significant correlation at $p<0.05$

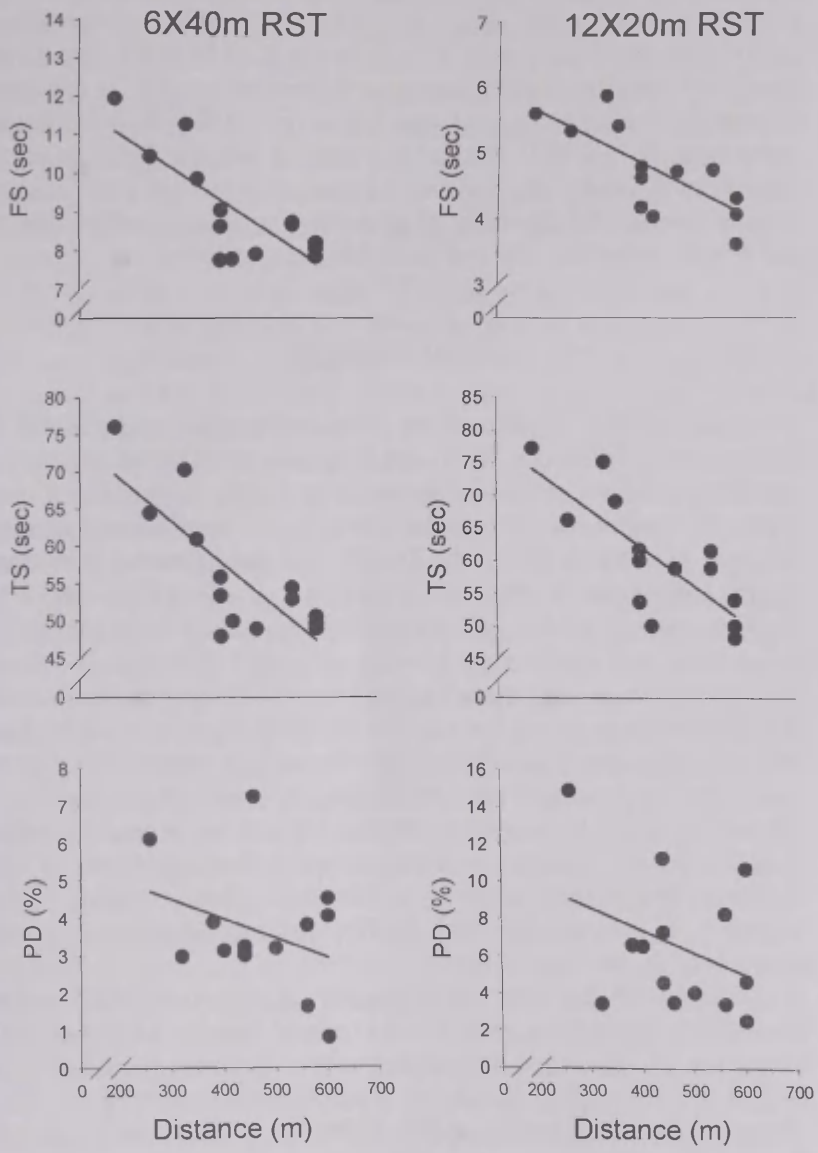

Figure 1. Relationships between the total distance in the 20m shuttle run and performance indices in the long (left panel) and short (right panel) RST.

Significant negative correlations were found between the 20 m shuttle run aerobic test and the total sprint time (r= –0.767) and the fastest sprint time (r= –0.738) of the short RST (12×20 m). Similarly, significant negative correlations were found between the 20 m shuttle run aerobic test and the total sprint time (r= –0.803) and the fastest sprint time (r= –0.787) of the long RST (6×40 m). There were no significant correlations between the performance decrement in the long or the short RST and the 20 m shuttle run aerobic test (r= –0.344 and r= –0.326 for the long and short RST, respectively).

DISCUSSION

The present study examined the relationship between performance indices of short (i.e., 12×20 m) and long (i.e., 6×40 m) interval RSTs, and aerobic fitness (measured by the 20 m shuttle run test) in pre- and early- pubertal overweight children. Despite the identical total running distance of the two RSTs, the TS, PD and total practice time were significantly higher in the short compared to the long RST. The RPE score was significantly higher in the short compared to the long RST. In addition, the maximal heart rate was higher (although not significantly) in the short compared to the long RST. These results indicate that performance of higher number of short repetitions with short recovery time was more difficult for overweight children than fewer but longer repetitions with relatively long recovery time. It seems that the physiological load of intermittent activity in overweight children depends on the specific variables, even if the total work of two different intermittent sessions is identical. These variables refer primarily to the number and duration of repetitions, and to the duration of the recovery periods.

Although we are unaware of studies that examined RST performance in overweight or obese children, several studies compared RST performances of normal weight children to adults [e.g., 17, 24, 25, 26]. Ratel et al. [24] found that prepubescent boys (9.6±0.7 yrs.) sustained their peak power output during ten 10 sec sprint exercises separated by 30 sec recovery intervals, while pubertal boys (15.0±0.7 yrs.) and young adult males (20.4±0.8 yrs) needed 5 min recovery intervals. In another study, Ratel et al. [25] found that running performance decreased less in boys (11.7±0.5 yrs) compared to men (22.1±2.9 yrs.) during ten repeated 10 sec treadmill sprints separated

by 15 sec recovery intervals. Three-minute recovery periods were sufficient for the boys to repeat short running sprints without substantial fatigue and a consequent performance decrement. In contrast, although the young men were able to modify their running style to maintain running velocity during the test, power and force output decreased significantly. Taylor et al. [29] suggested that the faster recovery in boys was due to their lower glycolitic activity and higher muscle oxidative capacity, allowing a faster re-synthesis of energy stores.

In the present study we tested a group of pre and early pubertal overweight children during two forms of RST. It was found that the PD was significantly higher in the short RST protocol (6.6% compared to 3.6% in the short versus the long RST protocol, $p<0.05$, Table 2). The decrement in running speed during the RST could be the result of a reduction in energy supply and/or acidosis of the muscle cell. The stores of phosphocreatine (PCr), which are essential to the reconstitution of short-term power output [7], could have been only partially replenished following each sprint, since a complete phosphagen recovery in children requires more than the 20 (short RST) or 40 sec (long RST) rest period that was used in the present study [7, 15]. However, the higher number of repetitions and the shorter recovery time probably made the short RST protocol more difficult compared to the long RST protocol. Yet the average sprint time in the long RST protocol was about twice that of the average sprint time of the short protocol. It is possible, therefore, that lactic acid accumulation and a feeling of local muscle fatigue would be greater following the long RST. Lactate levels were not measured in the present study; however, it is well known that exercise-induced lactic acid accumulation is markedly lower in pre-pubertal children compared to late-pubertal children and adults during repeated sprint exercise, due to their lower glycolytic energy turnover [12, 16]. This may explain the relative fast recovery and the lower PD of the overweight pre-pubertal children during the long RST in the present study. It is possible that if more sprints had been performed in the long RST, then fatigue and a significant decrease in performance would occur. Therefore, it seems that the length of the recovery time is a more significant factor than the length of the sprints during repeated activity in pre-pubertal overweight children. The results emphasize the need for selection of an appropriate RST protocol for performance assessment, one that will

match the activity characteristics and patterns of the specific population.

The PD values found in the present study are similar to PD values that were found among adult athletes in other studies [e.g., 4–6%; 10, 13, 32]. This supports the assumption that the recovery process among children is faster than in adults [7, 29], and that even overweight children are able to maintain exercise intensity relatively well throughout repeated sprints, in spite of their excessive weight and low aerobic capacity. In contrast, PD was higher in overweight children, indicating greater fatigue, compared to that of non-obese children, who were able to maintain their peak power with no significant reduction during RST [24, 25]. In addition, it should be emphasized that PD is determined relative to the personal results, which were far worse in the obese children of the present study compared to results in studies of non-obese children or adult athletes [9, 21, 31].

The present study also examined the relationship between the aerobic capacity (measured by the running distance of the 20 m shuttle run aerobic test) and the performance indices of the short and long RSTs. In contrast to our hypothesis, significant strong negative correlations were found between the aerobic capacity and the TS or the FT of *both* RSTs (see Table 3). Although PCr resynthesis appears to be controlled by the rate of oxidative metabolism within the muscle [29], previous studies have found only moderate correlations between VO_2 max and performance indices of RSTs [10, 14, 20,]. Glaister et al. [14] found moderate correlations between VO_2 max and power output regardless of recovery duration (10 or 30 sec) during repeated sprints. However, the relationships were stronger when power output data were averaged over all the sprints, supporting previous reports of moderate negative correlations between VO_2 max and total intermittent sprint time [1, 10]. These results are consistent with the present findings of strong negative correlations between aerobic capacity and the TS of both RSTs ($r = -0.803$ and $r = -0.767$, for the long and short RST, respectively; $p<0.05$). Moreover, aerobic capacity was significantly correlated to the FT of the participants in both RSTs as well ($r = -0.787$ and $r = -0.738$, for the long and short RST, respectively; $p<0.05$). These findings are in contrast to previous reports indicating that the aerobic components of a single short sprint ($\leq$10 sec) are very small (<10%) in adults subjects [5, 23]. Therefore, the results of the present study may suggest that oxidative metabolism plays an important role, serving as an energy source even during a

single sprint, in overweight children [16]. The magnitude of the correlation between FT and TS of both RSTs with aerobic capacity was unaffected by the differences in sprint length, sprint number, and recovery times between the long and short RST. This suggests that in overweight children other factors play an important role in these relationships (e.g., individual speed or anaerobic capacity). It also emphasizes again the need to find a protocol that will best fit the activities and the relationship between aerobic and anaerobic capacities of overweight children.

No significant correlations were found between the aerobic capacity and the PD of both RSTs in the present study (Table 3). This was somewhat unexpected in light of the strong correlations between aerobic capacity and the TS in both RSTs. However, while oxygen availability may influence fatigue during repeated sprints [3, 4], there is no substantial evidence of such link [1, 6, 10, 32]. Therefore, it is not surprising that correlations between VO_2 max and PD during RSTs have been inconsistent, and while some studies found significant correlations between the two [10], others failed to do so [32]. It is also possible that the magnitude of this association may be largely determined by the specific RST protocol. It could be hypothesized that the relatively short sprints in both RSTs in the present study resulted in only a partial depletion of the PCr stores. Therefore, the ability to re-synthesize these stores had no effect on the aerobic energy system. In contrast, in RST protocols involving longer (15–90 sec) high intensity sprints with longer recovery periods (1.5–7 min) and possibly greater depletion of PCr, the aerobic system had been shown to display significant correlations with fatigue and with total sprint time [10, 20]. The lack of correlation between aerobic capacity and performance decrement may also be explained by the heterogeneity of running skills and running efficiency among the pre-pubertal overweight children. Reduced running efficiency affects performance mainly during all out sprints, as was the case in both RSTs of the present study.

In summary, the physiological load of intermittent activity in prepubertal overweight children is significantly dependent on its specific variables even if the total work of two different intermittent sessions is identical. Specifically, performance of a high number of short repetitions with very short recovery time seems to be a more difficult task for overweight children than the performance of fewer longer repetitions with a longer recovery time. The significant correlations of

TT and FS of both RST protocols with aerobic capacity suggest that oxidative metabolism plays an important role in intense intermittent activity, even during a single all-out sprint in pre-pubertal overweight children. The lack of significant correlation between aerobic capacity and performance decrement during intermittent activity in overweight children suggests that factors other than aerobic fitness may be important for intensity maintenance during intermittent exercise in this population. Since activities of obese children are characterized by repeated short exercise bursts, performance of the traditional fitness tests like maximal oxygen consumption (10–12 min) or the Wingate anaerobic test (30 sec) does not represent their usual activity pattern, and RST may serve as another good alternative. More research is needed to select the best RST protocol for this population.

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ACID-BASE STATUS OF ARTERIAL AND FEMORAL-VENOUS BLOOD DURING AND AFTER INTENSE CYCLE EXERCISE

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ABSTRACT

Intense exercise depends on energy from both aerobic and anaerobic processes. These processes produce CO_2 and lactate, respectively, and both metabolites affect blood's acid-base status. To examine how the acid-base status of arterial and femoral-venous blood is affected and regulated, seven healthy young men cycled for 2 min at constant power to exhaustion. Blood samples were drawn from indwelling catheters in the femoral artery and vein during exercise and for 1 h after, and the samples were analysed for lactate (La^-), acid-base parameters, and plasma electrolytes (Na^+, K^+, Cl^-, La^-, HCO_3^-). The chloride concentration in red blood cells (cCl_{RBC}) was also determined to quantify the chloride shift. Arterial (femoral-venous, fv, mean values) blood lactate concentration rose to 13.8 mmol L^{-1} (fv 15.7), pH fell to 7.18 (fv 7.00), pCO_2 changed to 41 hPa (fv 114), and blood bicarbonate concentration was more than halved after exercise. cCl_{RBC} rose by 5 (a) and 8 mmol L^{-1} blood (fv) during exercise. pCO_2 and pH fell linearly by the lactate concentration. Consequently, blood bicarbonate concentration fell by 81% of the increase in blood lactate concentration, while blood base deficit rose 30% more than lactate did. Bicarbonate thus neutralised 62% of the total acid load. cCl_{RBC} rose in proportion to the amount of hydrogen ions buffered by haemoglobin, and chloride shift amounted to 31% of the total acid load. pH was lower and pCO_2 and bicarbonate concentration were higher in femoral-venous than in arterial blood with the same lactate

concentrations. The relationship between base deficit and blood lactate concentration did not differ between arterial and femoral-venous blood. In conclusion, after intense exercise pH falls more in femoral-venous than in arterial blood because of a lack of respiratory compensation of the metabolic acidosis.

Key words: acid-base balance, anion gap, arterio-venous difference, blood, buffering, chloride, chloride shift, electrolytes, exercise, lactate, pH, plasma.

INTRODUCTION

Intense exercise depends on anaerobic energy release, and breakdown of glycogen to lactate in the working muscles is quantitatively the most important anaerobic process [29]. Part of the lactic acid produced is released to the blood, thus reducing blood pH and altering its acid-base status [4, 24, 27, 33, 36, 43]. If exercise lasts for more than a few seconds, there is in addition a large aerobic energy release that leads to production of CO_2 that again may lead to a respiratory acidosis of venous blood. The blood may also receive hydrogen ions by a process independent of release of lactate or CO_2 from muscle to blood [2], possibly by a Na^+–H^+ exchange [24]. Each process contributes to acidification of the blood and thus to a drop in blood pH.

The relationship between the amount of lactic acid added to arterial blood and its acid-base status has been examined in several studies [4, 27, 33, 36]. It is thus well established that not only pH but also the CO_2-pressure (pCO_2) of arterial blood falls by the lactate concentration, meaning that there is a respiratory compensation for the metabolic acidosis introduced by lactate production. Venous blood may act as a closed compartment unable to reduce its pCO_2 and thereby buffer acids by bicarbonate. A raised pCO_2 will expectedly reduce the pH of venous blood considerably below that of arterial blood [16]; femoral-venous pCO_2 may double during strenuous exercise, reducing pH further by 0.2 below that of arterial blood [37].Further differences in the acid-base status between venous and arterial blood have apparently not been studied.

Acids added to the blood can be neutralised by bicarbonate as well be buffered as by several nonbicarbonate buffers where haemoglobin and plasma proteins are quantitatively the most important ones. The

contribution from each component in relation to intense, short-lasting, anaerobic types of exercise is not well known. Moreover, red blood cells can exchange bicarbonate with plasma chloride by the so called chloride shift mechanism [42]. The process is very fast, taking less than one second for equilibration [19]. However, the extent of this process in relation to high-intensity, anaerobic types of exercise has only been studied in arterialised blood [3], and possible differences between arterial and venous blood is therefore not known.

As pH falls, the net negative charge on plasma proteins is reduced, and anion gap of plasma would expectedly fall too. However, it has been suggested that anion gap may increase after intense exercise [27]. If so, other, unmeasured ions may perhaps appear in plasma, but this possibility has not been examined. On the other hand, our former study did not distinguished between concentrations of lactate and bicarbonate in plasma and in whole blood [27]. These ions are not evenly distributed in plasma and red blood cells, and that may have influenced conclusions drawn.

To examine changes in the acid-base status of blood further, healthy young men cycle for 2 min to exhaustion since this duration leads to a maximum anaerobic energy release [26, 29]. Blood samples were drawn from catheters in the femoral artery and vein during the exercise and at intervals for 1 h after. The samples have been analysed for lactate, acid-base parameters, and plasma electrolytes and the acid-base status of blood as well as red blood cell chloride concentration have been calculated.

MATERIALS AND METHODS

Subjects

Seven healthy male students at the Norwegian Police Academy volunteered to serve as subjects in this study after being given oral and written information about the experimental procedures and possible risks. The subjects were 25±2 yr old (mean ± SD), 1.85±0.04 m tall, weighed 81±4 kg, and their maximal O_2 uptake was 39±2 μmol kg^{-1} s^{-1} (53±3 ml_{STPD} min^{-1} kg^{-1}). The experiments were approved by The Ethics Committee of Health Region 1 in Norway.

Procedures

All exercise was carried out at a Krogh-type cycle ergometer [20] at a constant pedalling frequency of 1.5 Hz. The maximal O_2 uptake and the highest cycle power that could be kept for 2 min were determined for each subject during pretests the last weeks before the experiments.

Each subject arrived at the laboratory in the morning after an overnight fast. Catheters were inserted into the femoral artery and vein. Further details on the catherisation procedures and the experiments have been given in more detail elsewhere [24], see their Figure 1). In short, the subject warmed up for 15 min at a power corresponding to ≈50% of his maximal O_2 uptake. After a 10 min rest he cycled at a constant power established during the pretests for ≈2 min to exhaustion. Blood samples from the femoral artery and vein were drawn in parallel in 5 ml syringes before the exercise, after 30, 60 and 90 s of exercise, and at 30 s, 1, 3, 6, 10, 15, 20, 30, 45, and 60 min after the exhausting bout. The blood samples were handled as described elsewhere [24] to allow measurement of haematocrit (Hct), blood lactate (La) and haemoglobin (Hb) concentrations, blood acid-base parameters (pH, pCO_2, pO_2, sO_2), concentration of plasma electrolytes (Na^+, K^+, Cl^-, La^-, HCO_3^-), and plasma albumin, and proteins.

Analyses

Maximal O_2 uptake was established by the levelling-off criterion of Taylor et al. [40] using a discontinuous protocol of stepwise increases of cycle power, measuring the O_2 uptake during the last 30 s of a 3 min exercise bout at constant power. The expired volume was measured in a wet Tissot-type spirometer [41], and fractions of CO_2 and O_2 in the expired air was measured by analysers from Applied Electrochemistry Instruments (Pittsburgh, PA, USA).

Blood and plasma parameters were measured as described elsewhere [24, 25]. In short, the lactate concentration in plasma and whole blood was measured by enzymatic photofluorometry according to Passoneau and Lowry [34]. Blood pH, pCO_2, and pO_2 were measured on an IL 1312 blood gas manager (Instrumentation laboratory, Milan, Italy), while blood oxygen saturation (sO_2) was measured on an OSM 2 hemoximeter (Radiometer, Copenhagen, Denmark). Blood haemoglobin concentration (cHb) was measured by a hemiglobincyanide method of Baxter Dade AG (Düdingen, Switzerland). The

values are reported as concentrations in mmol L^{-1} of blood using a molecular mass of haemoglobin of 16.114 kDa. Blood haematocrit (Hct) was measured on blood samples in heparinised capillary test tubes centrifuged for more than 3 min at more than 15 000 g ($>1.5 \cdot 10^5$ m s^{-2}) on a Cellokrit 2 centrifuge (AB Lars Ljungberg, Stockholm, Sweden), thus giving a fraction of trapped plasma of ≈0.02 between the red blood cells [10, 11].

Plasma sodium, potassium, and chloride concentrations were measured on a Microlyte ion selective analyser (Kone corporation, Espoo, Finland). Plasma albumin concentration was measured by procedure 631 of Sigma Diagnostics (St. Louis, MO, USA) where albumin binds to bromcreosol green. The concentration of the product formed was measured in a spectrophotometer at 477 THz (628 nm) and expressed in SI-units using a molecular mass of albumin of 66.5 kDa [31]. The protein concentration was measured by the DC Protein assay method of Biorad laboratories (Hercules, CA, USA) using the two-step alkaline copper tartrate and folin reaction. The concentration of the product formed was measured in a spectrophotometer at 400 THz (750 nm).

The concentration of nine elements (Ca, Cu, Fe, K, Mg, Na, P, S, and Zn) in selected plasma samples were measured on an Optima 3000 inductive coupled plasma (ICP) emission spectroscopy analyser (Perkin Elmer, Norwalk, CT, USA). It appeared that the values of *c*Zn were 32 ± 5 μmol L^{-1}, which is 2–4 times the normal value. It is well known that in particular caps of test tubes like those used in this study may add zinc to plasma samples (Yngvar Thomassen, personal communication). Data on *c*Zn are therefore not given further consideration.

Calculations

Blood acid-base parameters were calculated along the principles of Siggaard-Andersen [39] as modified for use on modern computers [24]. The bicarbonate concentration is given as the "total" or titratable bicarbonate concentration that includes carbonate and carbamino compounds, both for plasma and for whole blood.

The (net) acid load on the blood was taken as the algebraic sum of the measured changes in the blood bicarbonate ($\Delta c HCO_3^-{}_B$) and blood base deficit ($\Delta c BD_B$) concentrations from the normal values of

19.5 mmol L^{-1} ($cHCO_3^-{}_B$) and 0 mmol L^{-1} (cBD_B, see Ref. [24] for further details):

[1] $$c\text{Acid load} = \Delta cHCO_3^-{}_B + \Delta cBD_B$$

After exercise the bicarbonate concentration fell, and the net acid load is thus less than base deficit and reflects the part of base deficit load buffered by other means than bicarbonate.

Plasma anion gap concentration was taken as

[2] $$cAG_P = cNa^+{}_P + cK^+{}_P - cCl^-{}_P - cLa^-{}_P - cHCO_3^-{}_P$$

Here La^- denotes lactate ions, and the index $_P$ means that all entities refer to concentrations in plasma.

Red blood cell chloride concentration was calculated as

[3] $$cCl^-{}_C = ([0.658 - 0.350\ \Delta pH_P] \cdot cCl^-{}_P) \cdot \phi_{w,C} / \phi_{w,P}$$

where cCl^- is the chloride concentration, the indices $_C$ and $_P$ refer to red blood cells and plasma, respectively, and $\phi_{w,C}$ and $\phi_{w,P}$ refer to the water fraction in the red blood cells and plasma, respectively. A separate analysis showed that the relative error of each estimated value was ≈ 2 mmol L^{-1} cell or 3% (not shown). The expression inside the curly brackets was taken from Funder and Wieth [8]. They expressed their concentrations on a molal basis (per kg of red blood cell or plasma water), while we report our values per litre of red blood cell or plasma volume. Conversions between mol L^{-1} and mol kg^{-1} water were done using water fractions of $\phi_{w,C} = 0.73$ and $\phi_{w,P} = 0.94$ for red blood cells and plasma, respectively, (p. 79 in Ref. [39], taken from Ref. [9] assuming a red cell density of 1.1 kg L^{-1}). It could be argued that if water leaves or enters the vascular bed or the red blood cells, the calculated values will be biased. However, if 10% of the plasma water was removed, water would still comprise 93.4% of the total plasma volume. Moreover, if 10% of the red cell water left the cell, water would still account for 70.9% of the red blood cell volume, showing that possible water fluxes have limited effect on the calculated intracellular concentration. Funder and Wieth [8] established the relationship above from measurements on fully oxygenated blood covering a large span of CO_2 pressures and pH-values, and only minimal deviations from the relationship were found [8]. Thus, the

equation was assumed to hold for our blood samples too. Possible deviations for venous blood with reduced O_2-saturation, are addressed in the discussion. Böning and co-workers [3] used a similar approach calculating cCl^-_C from a relationship proposed by Dell and Winters [6]. Their approach reported identical values of that proposed above when correcting for different water fractions ($\phi_{w,C} / \phi_{w,P}$).

The chloride concentration in red blood cells has been expressed per litre of whole blood by weighting (prescript w) for haematocrit (Hct), that is, the concentrations were multiplied by haematocrit:

[4] $$wcCl^-_C = cCl^-_C \cdot Hct$$

The effect of a reduced CO_2-pressure on acid-base status of the blood was calculated as follows: When pCO_2 is reduced, bicarbonate reacts with hydrogen ions, forming carbonic acid and CO_2. The hydrogen ions absorbed are taken from nonbicarbonate buffer bases (here symbolised as X' along with Ref. [39]. Thus, $dcHCO_{3\,B}/dpH_P = -dcX'_B/dpH_P = \beta X'_{B,P}$ (p. 45 in Ref.)[39]. The latter expression denotes here the buffer capacity of nonbicarbonate buffers in whole blood expressed for a unit change in plasma pH. It was calculated as explained elsewhere [24], and it appeared that $\beta X'_{B,P} \approx 29$ mmol L^{-1} pH^{-1} for the present data. Thus, an increase $\Delta cX'_B$ in cX'_B (and a corresponding decrease in the blood bicarbonate concentration) results in an increase in plasma pH of $\Delta pH_P = \Delta cX'_B/\beta X'_{B,P}$. The bicarbonate concentration of whole blood can be taken from the concentration in plasma and vice versa (see p. 46 in Ref. [39] or Ref. [24] for details), and consequently the bicarbonate concentration in plasma can be calculated from the new, lower bicarbonate concentration in whole blood. The new CO_2-pressure can now be calculated from the new pH_P and $cHCO_3^-{}_P$ by solving the Henderson-Hasselbalch equation for pCO_2. This procedure was iterated in steps of $\Delta cX'_B = 1$ mmol L^{-1} or $\Delta cHCO_3 = -1$ mmol L^{-1} to a pCO_2 of 53 hPa was found; a separate examination showed that steps much larger than 1 mmol L^{-1} did not introduce nonlinear effects (not shown). The amount of acid neutralised by reducing pCO_2 was taken as the difference between the initial and final bicarbonate concentrations of whole blood. The effect of increasing pCO_2 was calculated correspondingly. The numerical approach used is an Euler method [18] and was carried out in a spread sheet.

The *Bohr-Haldane effect* was taken as the reduction in O_2 saturation (sO_2) times blood haemoglobin concentration, using the Haldane coefficient $k_H = -0.31$ (p. 79 in Ref. [39]):

[5] $$\beta_{BH} = -k_H \cdot (1 - sO_2) \cdot cHb_B$$

Statistics

The data are given as mean ± SEM unless otherwise stated. Tests of statistical significance were carried out using *t*-tests. Linear regression was calculated as the geometric mean, thus taking into account that both parameters were subject to error [5, 35].

RESULTS

The subjects cycled at 5.48±0.17 W kg^{-1} for 122±7 s (mean ± SEM) to exhaustion.

Time course of blood lactate and acid-base parameters

The arterial blood lactate concentration rose during the exercise and peaked at 14 mmol L^{-1} in the interval 1–6 min after the exercise before declining (Figure 1a). The lactate concentration in femoral-venous blood was higher than that in arterial blood during the exercise and for the first 20 min of the recovery period. The lactate concentration in plasma was ≈60% higher than that in whole blood.

The bicarbonate concentration of both arterial and femoral-venous whole blood fell during the exercise and was around half the pre-exercise value in the early recovery before returning to the pre-exercise level in the late recovery (Figure 1c). The bicarbonate concentration in plasma was 20–25% higher than that in whole blood throughout the study. Thus for both lactate and bicarbonate the concentration in plasma was considerably higher than that in whole blood. Blood base deficit concentration rose during the exercise and further in the early recovery before returning to the pre-exercise value within 1 h of recovery (Figure 1e). In arterial blood standard base deficit was always within 1.0 mmol L^{-1} of the reported (actual) base deficit, and the changes in standard base deficit were in average 95% of those of (actual) base deficit (not shown further).

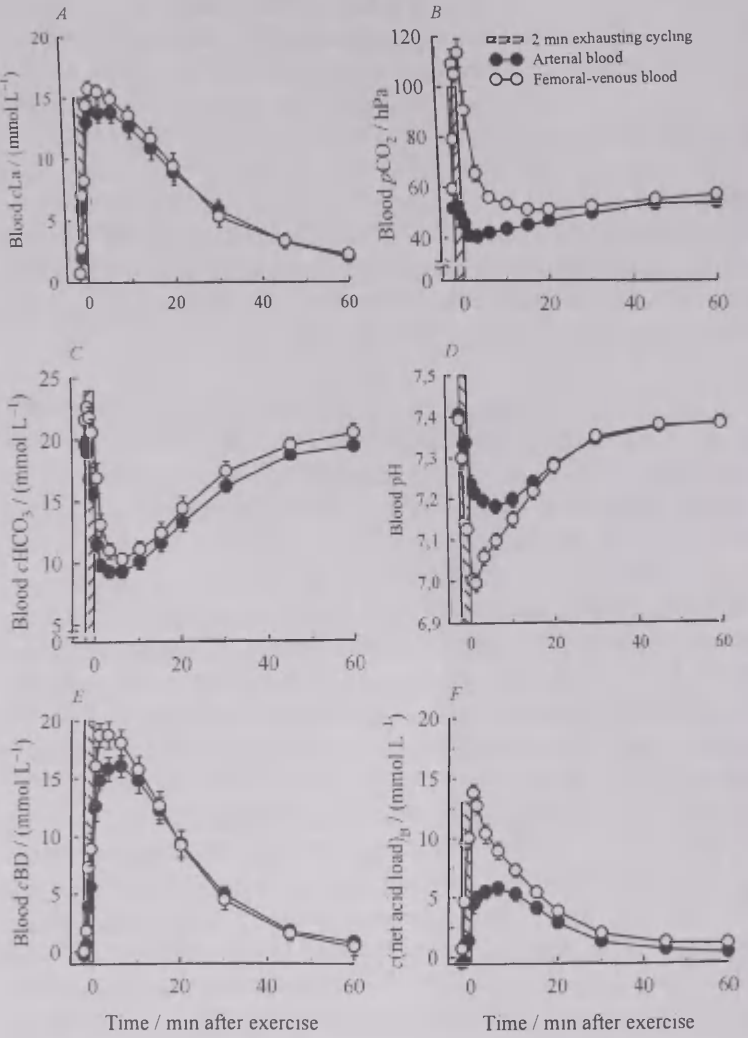

Figure 1. Blood lactate concentration and related acid-base parameters of arterial (●) and femoral-venous whole blood (○) during and after the exercise. *A*, blood lactate concentration (*c*La); *B*, blood CO_2 pressure (pCO_2); *C*, whole blood bicarbonate concentration ($cHCO_{3\ B}$); *D*, pH; *E*, blood base deficit (*c*BD); *F*, net acid load on whole blood [*c*(net acid load)$_B$]. The data are mean ± SEM of seven subjects during 2 min cycling at constant power to exhaustion and for 1 h after the exercise. Error bars not shown are hidden by the symbols.

The CO_2-pressure (pCO_2) of arterial blood fell during the exercise and further in the early recovery, while pCO_2 of femoral-venous blood doubled during exercise and dropped to below the pre-exercise level in the early recovery (Figure 1b). pCO_2 was back to the pre-exercise level within 45 min after the exercise.

pH of arterial blood fell during the exercise and further in the early recovery (Figure 1d). pH of femoral-venous blood fell twice as much, reaching a lowest value of 7.00±0.02 seen during the first minute of the recovery period. The arterial pH of 7.387±0.004 seen 1 h after exercise was still below the pre-exercise value (P=0.01).

The net acid load of the arterial blood rose during the exercise and further to a peak 6 min into the recovery period. The net acid load of femoral-venous blood rose more than twice as much (Figure 1f). One hour after exercise the net acid load of both arterial and femoral-venous blood was still above the pre-exercise level.

Table 1. Summary of the main blood values.

Parameter	Unit of	Before 2 min cycling		Just after 2 min cycling	
	measurement	Artery	Vein	Artery	Vein
cLa_B	mmol L^{-1}	0.7±0.2	0.7±0.2	13.0±0.7	14.2±0.8
pH		7.40±0.01	7.39±0.01	7.24±0.02	7.00±0.02
pCO_2	hPa	51.6±1.8	59.2±2.3	45.5±0.9	113.6±5.7
$cHCO_{3\,B}$	mmol L^{-1}	19.6±0.7	21.6±0.5	11.5±0.6	16.9±1.2
cBD_B	mmol L^{-1}	–0.3±0.6	0.0±0.6	12.4±1.3	16.4±1.7
cAcid load	mmol L^{-1}	–0.5±0.2	0.7±0.4	4.4±0.7	13.8±0.7
cHb_B	mmol L^{-1}	9.64±0.20	9.58±0.15	10.39±0.21	10.50±0.19
Hct		0.452±0.006	0.458±0.008	0.473±0.008	0.491±0.006
pO_2	hPa	137±5	57±5	149±3	43±10*
sO_2		0.963±0.006	0.670±0.056	0.965±0.007	0.291±0.102*
$cO_{2,B}$	mmol L^{-1}	9.3±0.2	6.4±0.6	10.0±0.2	3.1±1.1*
$cAlb_P$	mmol L^{-1}	0.640±0.013	0.652±0.024	0.714±0.020	0.791±0.032
$wcAlb_P$	mmol L^{-1}	0.351±0.008	0.353±0.012	0.377±0.012	0.396±0.012
ρPr_P	g L^{-1}	67.5±1.6	67.0±1.8	73.1±2.2	77.3±1.9

The data are blood lactate concentration (cLa_B), pH, CO_2-pressure (pCO_2), blood bicarbonate ($cHCO_{3,B}$), base deficit (cBD_B), and haemoglobin concentrations (cHb_B), blood haematocrit (Hct), O_2-pressure (pO_2), O_2-saturation (sO_2) and blood O_2-concentration ($cO_{2,B}$). All data refer to the values in whole blood. Further follows plasma albumin concentration ($cAlb_P$), plasma albumin concentration weighted for haematocrit ($wcAlb_P$) and plasma protein mass concentration (ρPr_P). The blood samples just after 2 min cycling were drawn 20–30 s after the end of exercise. pO_2, sO_2 and cO_2 of femoral-venous blood near the end of exercise were ≈30 hPa (pO_2), <0.2 (sO_2) and <2 mmol L^{-1} ($cO_{2,B}$). The data are mean ± SEM of seven subjects.

Blood haemoglobin concentration rose by 8% during the exercise, thus reflecting haemoconcentration (Table 1). The concentration fell in the recovery period, was back to the pre-exercise level within 15 min and below that level from 30 min after the exercise. Haematocrit of arterial blood rose during the exercise and peaked 7% above the pre-exercise value 3 min into the recovery. Haematocrit of femoral-venous blood was 9% above the pre-exercise level at exhaustion. Haematocrit fell to the pre-exercise level within 20 min and was below that level from 30 min into the recovery period.

The ratio between plasma albumin concentration weighed for haematocrit and blood haemoglobin concentration was 0.0367±0.0014 (mol Alb/mol Hb) before the exercise. There was at no time point any statistically significant arterial-femoral-venous difference for this ratio, nor did this ratio change during the exercise or in the recovery period. These data thus suggest that the vascular contents of albumin and haemoglobin were constant or changed in parallel during the study.

Scatterplots of acid-base parameters

pCO_2 and pH of the arterial blood fell by the blood lactate concentration (Figure 2A, C), and consequently the bicarbonate concentration of arterial blood fell by 0.8 mmol L^{-1} for a 1 mmol L^{-1} increase in the blood lactate concentration (Figure 2E). Arterial base deficit concentration rose 30% more than blood lactate concentration did (Figure 2G). These data thus show that in average bicarbonate and other, nonbicarbonate buffers each buffered 63% (HCO_3^-) and 37% (nonbicarbonate buffers), respectively, of the total acid load on arterial blood.

pCO_2 of femoral-venous blood ($pCO_{2,fv}$) doubled during the last minute of the exercise and stayed high for the first minute of the recovery period (Figure 1B). These values with a $pCO_{2,fv} > 80$ hPa are therefore marked separately in Figure 2 and are not included in the regression analyses. $pCO_{2,fv}$ was systematically higher than that of arterial blood with the same lactate concentration, and $pCO_{2,fv}$ showed no simple relationship to the lactate concentration (Figure 2B). pH of femoral-venous blood fell by the lactate concentration (Fig. 2D). Even when disregarding samples with $pCO_2 > 80$ hPa, pH in femoral-venous blood was 0.03–0.06 less than that in arterial blood with the same lactate concentration, and the relationship was slightly curved. The bicarbonate concentration of femoral-venous blood fell by the blood lactate concentration. When excluding samples with $pCO_2 > 80$ hPa, there was a relationship almost parallel to that of arterial blood but displaced to 1.7 mmol L^{-1} higher bicarbonate concentrations for the same lactate concentration (Figure 2F). The base deficit concentration of femoral-venous blood rose showed almost the same relationship to lactate concentration as seen in arterial blood, and there was no difference between samples with high and low pCO_2 (Figure 2H). When excluding samples with $pCO_{2,fv} > 80$ hPa, bicarbonate buffered 61% of all acid added to the femoral-venous blood, a value very close to that of arterial blood.

The dashed lines in *E* and *G* are lines of identity, that is, relationships assuming that each lactate ion added to the blood replaced one bicarbonate ion (*E*), and that each lactate ion added to the blood was accompanied by one and only one hydrogen ion (*G*). The difference between the solid and the dashed line in *G* thus shows the excess hydrogen ions added to the arterial blood. The dotted line in *G* is taken from the regression line in *E*, that is, by assuming that the amount of hydrogen ions added to the blood equalled the amount of bicarbonate ions disappearing. The difference between the solid and dotted line thus shows the amount of hydrogen ions buffered by nonbicarbonate buffers. The data are from seven subjects who cycled at constant power for 2 min to exhaustion and were followed for 1 h after.

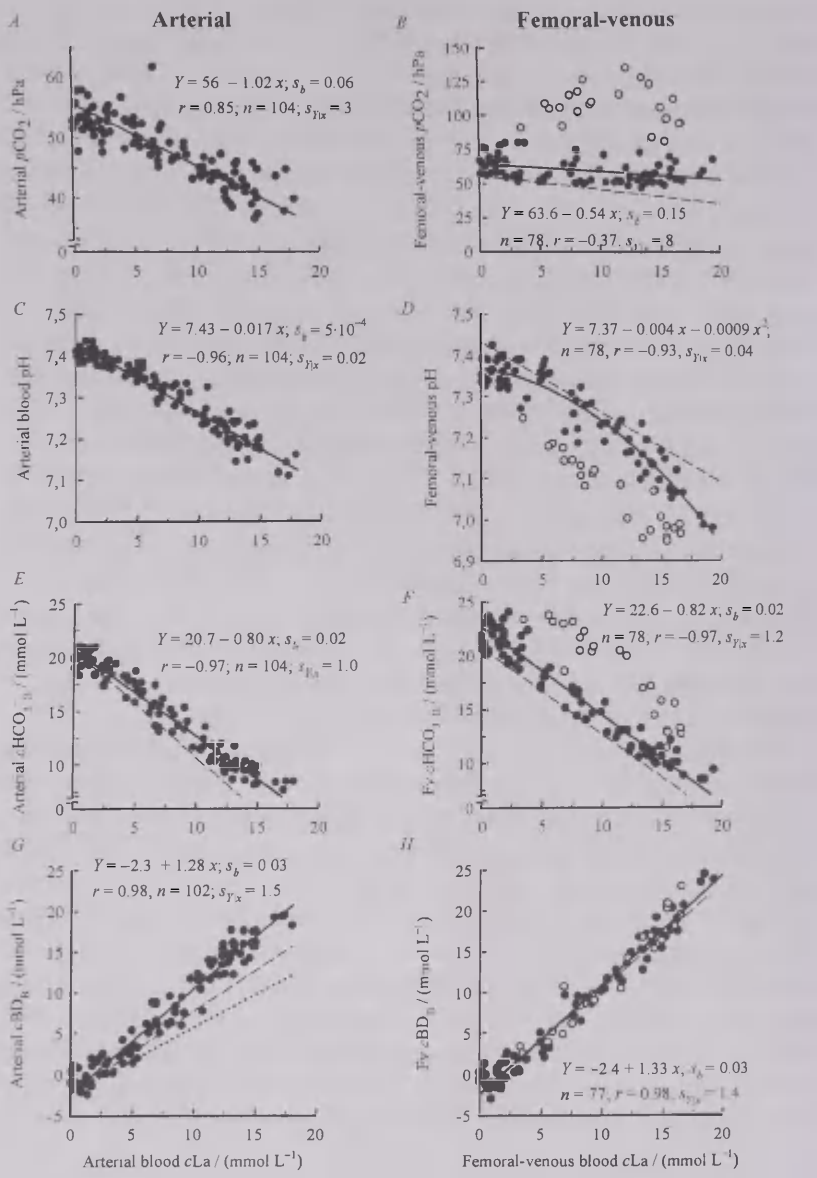

Figure 2. Arterial (left panels) and femoral-venous acid-base parameters (right panels) versus blood lactate concentration. Top row, blood pCO_2; second row, blood pH; third row, whole blood bicarbonate concentration; bottom row, blood base deficit. The solid lines are the regression lines

with the relevant regression parameters given in each panel. For femoral-venous plots (right) the corresponding regression line of arterial data is shown as a dashed line, and the difference between each pair of lines thus shows the difference between arterial and femoral-venous blood for the same lactate concentration. For femoral-venous blood ○ refers to samples taken during the last minute of the exercise and for the first minute after, that is samples with $pCO_2 > 80$ hPa ; these values are not included in the calculated regressions. ● refers to all other blood samples and on which values the regressions are based.

Plasma electrolyte concentrations

The plasma sodium concentration rose by 10 mmol L^{-1} during the 2 min exhausting exercise, mainly as a consequence of haemo-concentration during exercise, while the chloride concentration rose somewhat less (Table 2). The plasma potassium concentrations measured ≈30 s after the exercise was 2.3 mmol L^{-1} higher than before the ride. The plasma lactate concentration rose by 20 mmol L^{-1}, while the plasma bicarbonate concentration fell by around half this value (Figure 3A). Therefore, the sum of these two ion concentrations rose during the exercise, and more so for femoral-venous than for arterial plasma. Consequently, anion gap fell during the exercise, and more so for femoral-venous than for arterial plasma (Figure 3B). Anion gap rose linearly by pH, whether expressed in absolute terms (Figure 3C) or as anion gap weighted for changes in haematocrit [$wcAG_P$ / (mmol L^{-1}) = 6.8+13.3 (pH–7.4); $s_b = 0.8$; $s_{Y|x} = 1.1$; $r = 0.75$]. There was no difference between arterial and femoral-venous samples. One hour after the exercise all plasma electrolyte concentrations except those of lactate and bicarbonate were back to the pre-exercise values, and the anion gap was restored.

Table 2. Summary of plasma electrolytes and derived quantities.

Parameter	Unit of measurement	Before 2 min cycling		Just after 2 min cycling	
		Artery	Vein	Artery	Vein
cNa^+_P	mmol L^{-1}	134.5±1.2	135.3±1.1	143.9±1.9	147.0±1.9
cK^+_P	mmol L^{-1}	3.84±0.06	3.83±0.09	6.11±0.27*	6.21±0.39*
cCl^-_P	mmol L^{-1}	101.8±0.6	100.5±0.4	107.9±1.3	105.3±1.3
cLa^-_P	mmol L^{-1}	1.4±0.3	1.6±0.3	20.0±1.4	23.1±1.6
$cHCO^-_{3,P}$	mmol L^{-1}	24.0±0.6	26.6±0.8	14.1±0.8	20.2±1.4
cAG_P	mmol L^{-1}	11.1±0.7	10.3±0.7	8.1±1.1	4.7±0.8
cCl^-_C	mmol L^{-1}	57.8±0.3	59.0±0.2	66.1±0.9	70.4±0.8
$wcCl^-_C$	mmol L^{-1}	23.5±0.4	24.3±0.4	28.5±0.4	32.7±0.9

The data are plasma electrolytes (Na^+, K^+, Cl^-, lactate and bicarbonate), and anion gap (cAG_P). Finally, calculated concentration of chloride in red blood cells (cCl^-_C) and weighted for haematocrit ($wcCl^-_C$). * The blood samples just after 2 min cycling were drawn 20–30 s after the end of the exercise. cK^+_P near the end of exercise was ≈7 mmol L^{-1}. The data are mean ± SEM of seven subjects.

The ratio between the plasma sodium concentration weighted for haematocrit and blood haemoglobin concentration [cNa^+_P (1 – Hct) / cHb_B], was 7.7 ± 0.2 (mmol Na^+ / mmol Hb) for both arterial and femoral-venous blood before the exercise. The ratio fell to 7.3±0.2 (aP, –5%) and 7.0±0.2 (fvP, –9%) at exhaustion and stayed at those levels for the following 6 min. During this period there was a significant a–fv difference, compatible with an uptake of sodium in the leg (see Ref. [24] for further details and interpretation). Since we in the recovery period flushed the catheters with a heparinised isotonic NaCl-solution, changes later in the recovery are difficult to interpret physiologically, and further data are therefore not given.

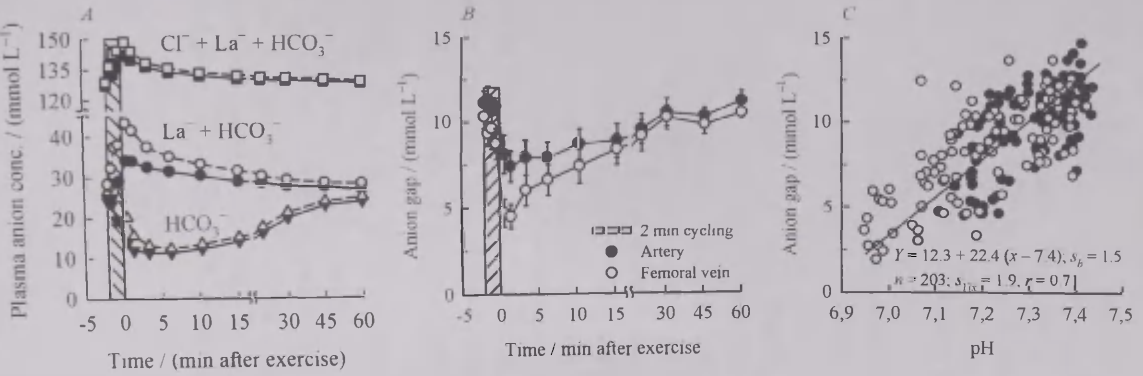

Figure 3. *A*, concentration of bicarbonate (HCO_3^-), lactate plus bicarbonate ($La^- + HCO_3^-$), and of chloride plus lactate plus bicarbonate ($CL^- + La^- + HCO_3^-$, sum of all measured anions) in arterial (filled symbols) and femoral-venous plasma (open symbols). *B*, plasma anion gap concentration, taken as $cAG_P = (cNa^+_P + cK^+_P - cCl^-_P - cLa^-_P - cHCO_3^-_P)$. *C*, plasma anion gap versus pH in arterial (●) and femoral venous (○) plasma. The data are from seven subjects cycling at constant power for 2 min to exhaustion and for 1 h after the exercise. In *B* the values are mean ± SEM; error bars not shown are hidden by the symbols (SEM ≈1 mmol L^{-1}).

In arterial blood the relationship between plasma bicarbonate and lactate concentrations was $cHCO_{3,aP}$ = 25 mmol L^{-1} – 0.65 cLa_{aP} (s_b = 0.02, $s_{Y|x}$ = 1.7 mmol L^{-1}, n = 105, r = –0.95). The corresponding relationship for plasma from femoral-venous blood was $cHCO_{3,fvP}$ = 27 mmol L^{-1} – 0.63 cLa_{aP} (s_b = 0.02, $s_{Y|x}$ = 1.8 mmol L^{-1}, n = 74, r = –0.95) when samples with a pCO_2 > 80 hPa were excluded. The slopes of the two relationships do not differ. Thus, in average a 1 mmol L^{-1} increase in the plasma lactate concentration resulted in a 0.64 mmol L^{-1} drop in the plasma bicarbonate concentration.

Concentrations of eight elements in plasma. The concentrations of eight elements in plasma (Ca, Cu, Fe, K, Mg, Na, P, and Sn) were measured before the exercise and 1 min after the exercise. There was no major change during the exercise nor any major a–fv differences, and the moderate changes and differences seen are compatible with haemoconcentration and the fluid shift that took place.

Red blood cell chloride concentration

The calculated chloride concentration rose by 8 (+15%) and 12 mmol L^{-1} (+23%) for arterial and femoral-venous red blood cells, respectively, during the exercise. To correct for fluid shifts between plasma and red blood cells, the concentration were expressed per litre of whole blood by weighing the concentrations expressed per litre of cell volume for haematocrit. The weighted chloride concentration rose by 21% (a) and by 34% (fv) during the exercise (Figure 4A, Table 2). The chloride concentrations of red blood cells fell in the recovery. From 10 min into the recovery period the weighed chloride concentration of femoral-venous red blood cells did not differ from that of arterial blood.

The weighted chloride concentration of red blood cells rose linearly by the net acid load on blood and by reduced pH (Figure 4 B, C). The weighed chloride concentrations of the red blood cells was in average 0.6 mmol L^{-1} less in femoral-venous than in arterial blood for the same blood pH or acid load. The calculated chloride uptake of the red blood cells amounted to 82% of the net acid load on the blood (Figure 4B).

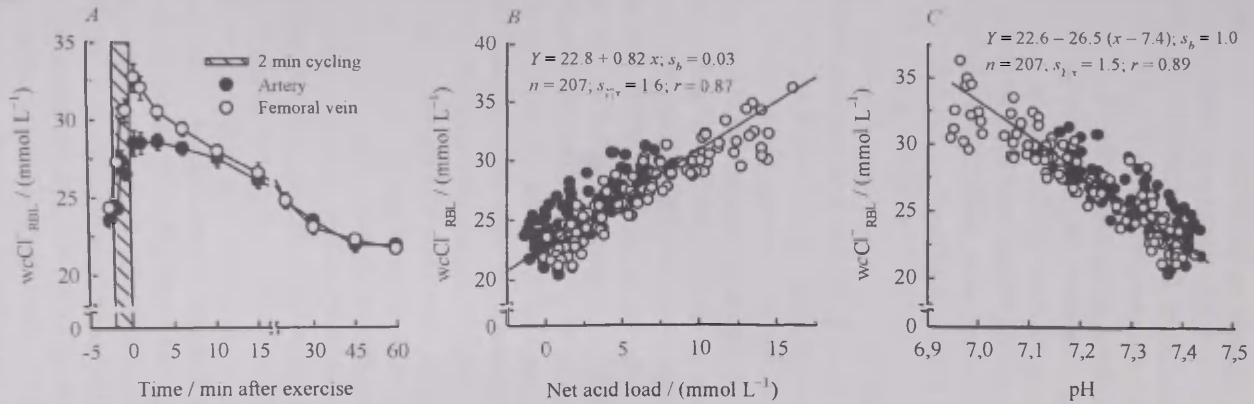

Figure 4. *A*, weighted red blood cell chloride concentration for seven subjects during 2 min cycling to exhaustion and for 1 h after. The data are mean ± SEM, and error bars not shown are hidden by the symbols. *B*, weighted red blood cell chloride concentration versus net acid load on the blood. *C*, weighted red blood cell chloride concentration versus pH. The chloride concentration of red blood cells was calculated as explained in the method section, and weighted values given are expressed per volume of whole blood by multiplying the red blood cell concentrations by haematocrit. The data are from seven subjects who cycled at constant power for 2 min to exhaustion.

DISCUSSION

Blood pH fell by increasing blood lactate concentrations, and more so in femoral-venous blood with either an additional respiratory acidosis or only limited respiratory compensation. Blood base deficit concentration rose 30% more than the blood lactate concentration did, and the relationship did not differ between arterial and femoral-venous blood with different pCO_2. Bicarbonate buffered in average 62% of the hydrogen ions added to the blood. Chloride left the plasma space and entered red blood cells in proportion to the net acid load or change in pH and amounted to >30% of the total acid load. Plasma anion gap fell linearly by a falling pH or increasing acid load.

Comparison with former studies

Blood lactate concentration rose during the exercise and continued to rise for a few minutes into the recovery period and fell thereafter. This pattern and the values seen are in line with several former studies [3, 4, 24, 27, 33, 36, 43]. Blood and plasma bicarbonate concentration fell linearly by the lactate concentration, which is in line with data from former studies [4, 27, 33]. In arterial blood pCO_2 fell linearly by the blood lactate concentration or the degree of acidosis, as has also been shown earlier [27]. Thus, our data on arterial blood are in line with former studies. During exercise there was no respiratory compensation in femoral-venous blood but in fact a doubling of the pCO_2 near the end of the exercise and in the early recovery, thus adding a respiratory acidosis to the metabolic one. That observation is in line with that of Sahlin and coworkers [37]. Finally, the observed changes in plasma chloride concentration are in line with a recent study [3]. Thus, when comparisons are possible, our data are in line with former studies and thus appear typical for very intense exercise. Consequently, it is therefore conceivable that further analyses and calculations on our data are not atypical.

Acid-base status of arterial and femoral-venous blood

For arterial blood pH, pCO_2, and the bicarbonate concentration all fell linearly by increasing lactate concentrations, while base deficit rose linearly by the lactate concentration. For femoral-venous blood there were corresponding relationships between pH and bicarbonate concentration versus blood lactate concentration when samples with particularly high pCO_2 were excluded. The relationship between blood

base deficit and blood lactate concentrations did not differ systematically between arterial and femoral-venous blood, nor did base deficit differ between samples with high and low pCO_2. The latter observation suggests that respiratory acidosis or alkalosis had no influence on the calculated base deficit concentration, which was to be expected since base deficit measures the metabolic or nonrespiratory component of the acidosis in blood. The finding that base deficit did not differ between arterial and femoral-venous blood with the same lactate concentration even when pH differed, suggests that the differences in pH and acid-base status between arterial and femoral-venous blood was due to different degrees of respiratory acidosis or compensation.

Just after exercise pH differed by as much as 0.2 between arterial and femoral-venous blood, and the main reason was different pCO_2, as has been shown earlier [36]. These results thus show the importance of pCO_2 for blood pH, as has been addressed in a recent review [16].

Base deficit and excess hydrogen ions

Blood base deficit changed ≈30% more than the blood lactate concentration did. This is compatible with the idea that also hydrogen ions of nonlactic and noncarbonic origin appeared in the blood. It was first suggested that lactate and hydrogen ions appeared in equal amounts in the blood [43]. Later studies found that base deficit exceeded the blood lactate concentration after intense exercise. One interpretation was that the excess seen meant that base deficit overestimated the amounts of hydrogen ions added to blood [4, 33]. It was later shown that there was an excess of hydrogen ions added to blood in the early recovery period after intense exercise [2, 27, 36], at the same time as muscle pH recovers much faster than muscle lactate concentration does [13, 14, 38], compatible with the idea that muscle removed hydrogen ions to the blood independently of lactate ions in the early recovery after intense exercise. It is now known that muscle can release hydrogen ions independently of lactate [2, 17, 21]. We have more recently shown that in the leg sodium ions left plasma in equal amounts to the excess hydrogen ions appearing in the blood after intense exercise [24]. Those data are compatible with an activation of a Na^+,H^+-exchange in the early recovery, which is well established to take place for the amiloride-sensitive Na^+,H^+-exchanger when muscle pH is reduced [21]. Thus, we now know that base deficit is an accurate measure of the metabolic acidosis in blood and that the

excess hydrogen ions appearing in the blood after exercise is a physiologic phenomenon reflecting processes with well established mechanisms.

The view of excess hydrogen ions released to blood has recently been questioned by Böning and co-workers who found that changes in standard base deficit, assumed to measure metabolic acidosis averaged over the whole extracellular compartment, equalled the calculated extracellular lactate concentration [3]. Their approach assumes sufficiently fast equilibration of lactic acid and bicarbonate in all extracellular space, which may not be the case [30]. A further discussion of possible excess release of hydrogen ions is beyond the scope of the present paper.

Uptake of chloride in red blood cells

Chloride left plasma and entered the red blood cells in proportion to the change in pH and to the net acid load. Chloride shift and its relation to pCO_2 and blood acid-base status has been known for more than hundred years [12, 32]. The phenomenon was later shown to be due to a property of red blood cells and not of plasma [7], to be a chloride-bicarbonate-exchange across the red cell membrane [15], and to be a very fast process, reaching equilibrium within 1 s [19, 42]. Bicarbonate neutralised most of the hydrogen ions added to the blood, but of the remaining hydrogen ions added, our data suggest that 82% could be accounted for by processes related to chloride uptake in red blood cells. Thus, the calculated chloride shift amounted in average to 31% of the total acid load on the blood.

At each time point the chloride concentration in red blood cells was higher in femoral-venous than in arterial blood. That observation is compatible with an uptake of chloride by the red blood cells in exchanged with bicarbonate in the peripheral capillaries (and a reversal in the lungs). Our data show in addition that the chloride concentration in red blood cells rose by a falling pH or an increasing net acid load. Since plasma bicarbonate concentration fell during these conditions, this means that the cells took up chloride during acidosis while the bicarbonate concentration in plasma fell. It is likely that excess hydrogen ions in plasma have reacted with bicarbonate, thus forming CO_2 that have diffused into the red blood cells, formed bicarbonate that again have been exchanged with chloride in plasma, a process known as the Jacobs-Steward cycle [15]. The process may

take place even without carbonic anhydrase available in plasma, but then requiring 1 min or more for approaching equilibrium.

The chloride concentration in red blood cells was in this study not measured but calculated from the measured pH and plasma chloride concentration using equation [3] taken from [8]. Funder and Wieth established their relationship from measurements covering a large span of pCO_2- and pH-values, but only on fully oxygenated blood. They found no systematic deviations from the relationship they established, and a separate analysis on their data showed that the error in each estimate was $\approx$2 mmol L^{-1} or 3%. Dell and Winters [6] developed the same relationships using others data. Thus, two independent sets of data support our calculated chloride concentrations. Others have calculated the chloride concentration of red blood cells from the measured amounts of chloride in haemolysed whole blood and plasma [22, 23]. That approach that is less precise than direct measurements but would expectedly not introduce systematic errors. The chloride concentration of red blood cells in two other studies rose almost as much as in our study [3, 23]. Thus, these studies give further support to our data on the red blood cell chloride concentration calculated from equation [3]. However, as discussed below, our calculations may have underestimated the uptake in red blood cells of deoxygenated femoral-venous blood. Thus, in future studies red blood cell chloride concentration should be measured directly, at least in deoxygenated venous blood.

Plasma electrolyte balance

The pooled concentration of cations and anions in plasma rose during the exercise, and the plasma volume fell, as shown by the increased albumin concentration. Haemoconcentration is one major reason for the increases in plasma electrolyte concentrations. However, several factors modified this picture. Most important is that during the exercise and for the first minutes after lactate replaced bicarbonate in plasma at a ratio of $\approx$1 : 0.64 (mot including femoral-venous samples with pCO_2 > 80 hPa). In addition, both sodium and chloride left the plasma space. While sodium was probably taken up by acidotic muscle cells in exchange with H^+ [24] chloride was most likely taken up by the red blood cells. Finally, the plasma potassium concentration rose during the exercise and fell in the early recovery period, as studied in much more detail elsewhere [28].

The concentration of anions raised more than the concentration of cations did, mainly because of the smaller loss of bicarbonate than accumulation of lactate. Consequently, plasma anion gap concentration fell linearly by a falling pH or by an increasing net acid load, that is, by an increasing lactate concentration. That finding is in apparent conflict with our former study where we reported an apparent increase in the calculated anion gap after the exercise [27]. However, in that study we compared the lactate concentration in whole blood with the concentration of bicarbonate and other electrolytes in plasma. In the present study the plasma lactate concentration was as much as 10 mmol L^{-1} higher than the concentration in whole blood, and this difference may explain the whole difference between the two studies.

Anion gap reflects the net negative electric charge on electrolytes that have not been measured, preferentially on plasma proteins. It could be that plasma exchanged other ions. That possibility was examined by measuring the concentrations of eight elements in plasma samples taken before the exercise and 1 min into the recovery. These analyses showed only moderate changes in the concentration of each of the measured elements, compatible with haemoconcentration and fluid shift and thus suggest that there was no detectable exchange between muscle, plasma, and red blood cells of the measured elements or ions other than sodium, potassium, chloride, lactate, and bicarbonate. Moreover, the production and release of pyruvate from muscle is minimal [4, 36]. However, anion gap fell by 22.4 mmol L^{-1} for a unit drop in plasma pH. If that value did reflect buffering by plasma proteins, the slope would correspond to a buffer capacity of >0.3 mmol pH^{-1} g^{-1} protein, which is three times the value found by others by titration of plasma (p. 42 in Ref. [39]). A correction for changes in the protein mass concentrations during the study has no influence on this conclusion (not shown). Thus, it could also be that the concentration of other ions in plasma, perhaps some organic ions, was changed after the exercise. The results of a change in anion gap in excess of changed charge of plasma proteins is in line with data of Adrogue and co-workers [1] who also proposed changes in unmeasured organic anions as a likely explanation.

The ratio between blood concentrations of albumin and haemoglobin was constant throughout the study, meaning that the vascular content of both species was probably constant, apart from loss due to blood sampling. The mass concentration of plasma proteins rose relatively less than the albumin concentration. That observation is

compatible with loss of plasma proteins other than albumin during exercise and in the early recovery, as also suggested by another study [22].

Neutralisation of acids added to the blood

In femoral-venous blood base deficit rose by 20 mmol L^{-1} at the extreme. Blood pH fell from 7.4 to 7.0, which is an increase in the activity of hydrogen ions from 40 to 100 nmol L^{-1}. Using an activity coefficient of 0.84 (p. 28 in Ref. [39], this corresponds to an increase in the concentration of free hydrogen ions of ≈70 nmol L^{-1}. This means that for each million of hydrogen ions added to the blood, less than four remained free at any time while the others were neutralised. A corresponding calculation for the data on arterial blood shows that less than three out of one million hydrogen ions released to the blood were free. Blood has several means of neutralising added acids. Bicarbonate may react with hydrogen ions, form carbonic acid that again is split to water and CO_2 that may be lost through the lungs. It appeared that ≈62% of the total acid load, taken as the base deficit, was neutralised by bicarbonate in both arterial and femoral-venous blood (disregarding samples with $pCO_2 > 80$ hPa). Thus, bicarbonate was quantitatively the most important means of neutralising acids added to the blood.

Our data suggest that of the portion of hydrogen ions added to the blood but not neutralised by bicarbonate, 82% entered the red blood cells by a chloride shift and were buffered intracellularly. That amounts in average to 31% of the total acid load (base deficit). Thus, other means accounted for only 7% of the total acid load.

The magnitude of base deficit, its components and how this acid load was accounted for, is shown in Figure 5. In arterial samples reduction of blood bicarbonate concentration neutralised in both cases 61% of the acid load, taken as the base deficit concentration. The main component was due to the effect of a reduced bicarbonate concentration as pH fell, keeping the CO_2-pressure constant. As a consequence of hypervention pCO_2 of arterial blood fell to 41–45 hPa, which reduced the bicarbonate concentration further by ≈1 mmol L^{-1} and thus neutralised the same amount of hydrogen ions. In femoral-venous blood pCO_2 was increased, and that led to an extra acid load of to 5.3 mmol L^{-1} (0 min, fv) and 0.4 mmol L^{-1} (6 min, fv).

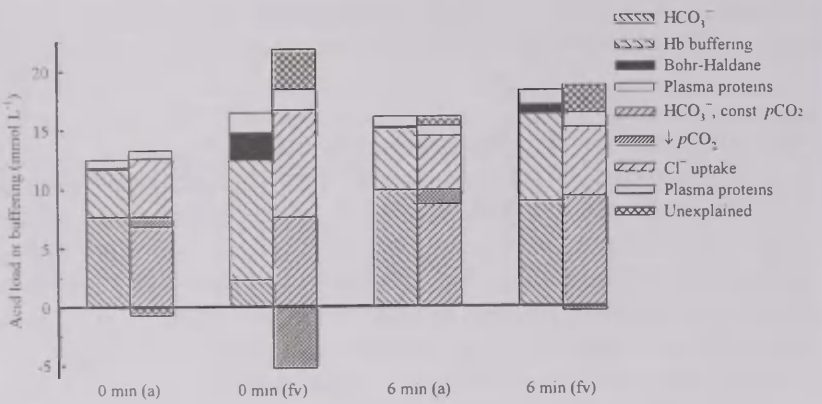

Figure 5. *Left column* in each pair, components of base deficit taken as (bottom to top) a reduced bicarbonate concentration in whole blood (HCO_3^-), buffering on haemoglobin without the Bohr-Haldane effect (Hb buffering), the Bohr-Haldane effect (Bohr-Haldane), and buffering by plasma proteins (Plasma proteins). *Right column* in each pair, to what extent the base deficit was reflected in a reduced bicarbonate concentration at a constant pCO_2 (HCO_3, const. pCO_2), by a reduced pCO_2 ($\downarrow pCO_2$), by the calculated uptake of chloride in the red blood cells (Cl^- uptake), by buffering by plasma proteins (Plasma proteins), and finally the difference between the base deficit and the sum of the components above (Unexplained). The data are mean values of seven subjects who cycled at constant power for 2 min to exhaustion. The values are for arterial (a) and femoral-venous (fv) blood just after the cycling (0 min) and 6 min after the exercise (6 min). The chloride concentration of the red blood cells and the effect of a reduced or increased CO_2-pressure were calculated as explained in the method section; for femoral-venous blood with a raised CO_2-pressure this component came out negative. Base deficit and its components were calculated as explained elsewhere [24].

In arterial blood haemoglobin neutralised 33% of the hydrogen ions, but the Bohr-Haldane effect was minimal. In femoral-venous blood haemoglobin neutralised 76% (0 min fv) and 45% of the acid load (6 min fv). Those percentages include contributions by the Bohr-Haldane effect of 14% (2.3 mmol L^{-1}, 0 min fv) and 4% (0.7 mmol L^{-1}, 6 min fv) of the total neutralisation . Thus, for femoral-

venous blood just after the exercise the Bohr-Haldane effect neutralised more hydrogen ions that bicarbonate did.

For arterial blood the calculated chloride uptake in red blood cells was similar to the amount of hydrogen ions neutralised by haemoglobin; the small mismatch seen are well within the analytical errors. For femoral-venous blood there was an apparently unexplained component of 3.4 mmol L^{-1} (0 min fv) and 2.3 mmol L^{-1} (6 min fv). The chloride concentration of the red blood cells was in this study calculated, using equation [3] worked out for fully oxygenated blood and thus disregarding the Bohr-Haldane effect. If hydrogen ions neutralised by the Bohr-Haldane effect is included, the apparent mismatch is largely within the error of analysis and estimation.

Neutralisation by plasma proteins accounted for 10% of the base deficit in femoral-venous blood just after the exercise and 5–6% in the other samples shown.

CONCLUSION

Bicarbonate neutralised most of the acids added to the blood, and haemoglobin neutralised most of the remaining part. Base deficit did not differ between arterial and femoral-venous blood with the same lactate concentration. The acid-base status of femoral-venous and arterial blood differed because of different degrees of respiratory acidosis or compensation. The chloride concentration of red blood cells rose in proportion to the amount of hydrogen ions buffered by haemoglobin.

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RELATIONSHIP BETWEEN ANTHROPOMETRIC PARAMETERS, PHYSIOLOGICAL RESPONSES, ROUTES AND COMPETITION RESULTS IN FORMULA WINDSURFING

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ABSTRACT

Formula windsurfing is faster than the Olympic version, due to a number of unique differences. This study was designed to identify the importance of anthropometric and cardiac factors on the final result of the European Formula Windsurf Championships (2007). We selected 45 competitors (30 amateurs and 15 professionals) of 30±9.77 years of age, a height of 182.6±0.06 cm, a weight of 81.67±7.35 kg and a BMI of 24.7±2.1 kg. They were divided into three groups (PG: 15; TG: 45 and GPSG: 12). We followed the recommendations of Carter and Marfell-Jones for the anthropometric measurements. The route, speed, distance and heart rate were recorded using an FRWD W600 GPS (Global Positioning System) unit. The anthropometric measurements indicate a professional profile with 2.3±0.4 endomorphy 5±0.8 mesomorphy and 2.4±0.6 ectomorphy. Arm span and fat mass show a significant ($p \leq 0.02$) and very significant ($p \leq 0.005$) correlation with the final classification. The average speed was 11.84±2.38 $km \cdot h^{-1}$, the heart rate varied from 128 to 180 $b \cdot min^{-1}$ and the average was 127.62±13.73 $b \cdot min^{-1}$. The distances covered (12784.77±5522.19 m) and the times used for the races (2049.3±989.68 s) were very variable. This will assist not only in initial selection for the sport, but also in the

design of training programmes which further develop that morphology, where possible, in the pursuit of improved performance.

Key words: somatotype, anthropometric, windsurf, heart rate, GPS

INTRODUCTION

Windsurfing dates back to 1935, when Tom Blake, one of California's leading surfers, inserted a device into his 14-foot concave board. Seventy-eight years have passed since those beginnings of a new sporting discipline. Nowadays windsurfing is an Olympic sport and has been part of the list of sailing sports since the 1984 Los Angeles Olympics. It is now in an enviable position, with numerous participating countries, converting it into an attractive sport that is in direct contact with the environment.

Windsurfing has shown itself to be a highly demanding discipline. While sailing, the heart rate increases with wind speed from 60 to 200 beats per minute [18]. De Vito et al. [8] showed that when sailing with a wind speed of 4–5 $m \cdot s^{-1}$, average value for oxygen consumption was 43±4 $ml \cdot min^{-1} \cdot kg^{-1}$ (73% of HR_{max}) and the average heart rate (HR) was 169±12 $b \cdot m^{-1}$ (92% of HR_{max}). The physiological demands appear to be influenced by the strength of the wind. During Olympic races with light winds (3–5 $m \cdot s^{-1}$), it has been shown that average heart rate during competition is 167 $b \cdot m^{-1}$, while average lactate concentration is 8.5 $mmol \cdot l^{-1}$ [1, 6]. However, in the same conditions with stronger winds (12–15 $m \cdot s^{-1}$), average heart rate is 154 $b \cdot m^{-1}$, with a lactate concentration of 2.9 $mmol \cdot l^{-1}$. These figures suggest that, in light wind conditions, there are less physiological and metabolic demands. This may be due to the permanent pumping action needed to increase the speed of the boat when the wind is not strong enough. Other authors, such as Vogiatzis et al. [20], showed that the pumping action needed to sail with a wind speed of between 4 and 15 $m \cdot s^{-1}$ leads to a significant increase in the physiological and metabolic demands on the sportsperson (from 19.2 to 48.4 $ml \cdot min^{-1} \cdot kg^{-1}$ and from 110 to 165 $b \cdot m^{-1}$, respectively). It has also been shown that improved performance in the laboratory is highly correlated with the increased amount of time spent at high speeds on the board [7].

At present, among the various international federations promoting windsurfing, the IWA (The International Windsurfing Association) is

the organisation that unifies the sport. The association was founded in the UK in January 2001 and its aims include organising such competitions as the Formula Windsurfing European Championships. This class of windsurfing is regarded as the fastest in the world, largely due to the difference in the size of the sail when compared with Olympic windsurfing (12.5 and 9.5 metres respectively).

These differences may make different demands on sportspersons participating in the Formula and Olympic windsurfing classes. In this sense, this study is designed to identify the importance of anthropometric factors and physiological responses on the final classification of the 2007 European Formula Windsurfing Championships.

MATERIALS AND METHODS

The European Formula Windsurfing Championships held at Santa Pola (Spain) included the Qualifying Race for participation in the 2007 World Formula Windsurfing Championships. The championships were organised by the Santa Pola Windsurf Club and the Spanish Royal Sailing Association (RFEV). The championships were governed by ISAF (International Sailing Federation) regulations and the Racing Rules of Sailing (RRS).

Subjects

89 Caucasian males from 18 countries took part in the championships with 45 windsurfers being chosen for the study. Their characteristics were as follows: age 30±9.77, height 182.6±0.06 cm, weight 81.67±7.35 kg and body mass index 24.7±2.1 kg. All the subjects were informed of the tests and measurements that were going to be carried out and gave their written consent.

The chosen subjects were divided into three groups:

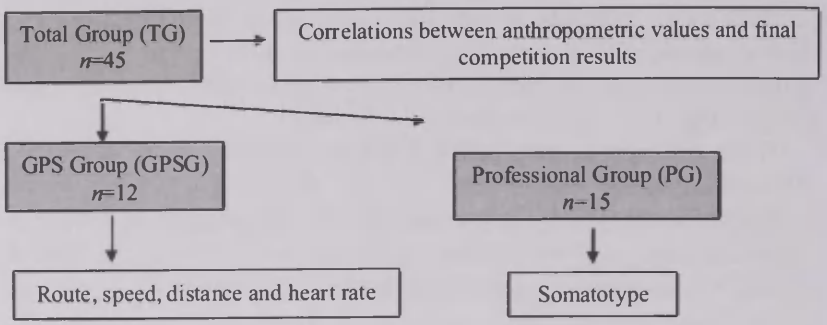


Figure 1. Distribution of the groups for the different aims of the study.

Procedure

A field laboratory was set up in the race area to take the measurements in real competition conditions.

A field laboratory was located in the regatta area in order to allow measurements to be taken as close to competition time as possible. The 45 male participants were categorised as Professionals (n=15) or Amateurs (n=30). All anthropometric measurements were taken in the same tent at an ambient temperature of (22±1°C) by the same investigator, an International Society for the Advancement of Kinanthropometry (ISAK) Level 2 anthropometrist. Measurements followed the protocols of Marfell-Jones et al. [15], and Marfell-Jones [14]. Measurements were taken three times for each subject. The equipment used included a Holtain skinfold calliper (Holtain Ltd. UK), a Holtain bone breadth calliper (Holtain Ltd. U.K), scales, stadiometer and anthropometric tape (SECA LTD., Germany). The physical characteristics were measured in the following order: age, weight, stature, arm span. The following measurements were also taken: sitting height, acromiale height, radiale height, dactylion height, tibiale height, biacromial breadth, biiliocristal breadth, humerus and femur width; pectoral, subscapular, biceps, triceps, suprailiac, supraspinale, front thigh, medial calf and abdominal skinfolds.

Muscle mass was calculated using the Lee equation [13]. Fat mass was calculated using for the Withers equation [21]. Bone mass was calculated using the Döbeln equation, modified by Rocha (as cited in

Carter & Yuhasz [5]). Somatype was calculated using the Heath-Carter equations [4].

In order to record the route (latitude and longitude), speed ($km \cdot h^{-1}$), distance (m) and heart rate ($b \cdot m^{-1}$) during the different heats valid for the final classification in said championships; a GPS unit (FRWD W600 Global Positioning System (12-channel GPS receiver; location measurement accuracy < 3 m; distance accuracy > 99%; speed measurement accuracy < 0.2 $m \cdot s^{-1}$; heart rate measurement accuracy ±1 $b \cdot m^{-1}$; 30–240 $b \cdot m^{-1}$ heart rate range; dimensions 95×55×15 mm; weight 85 g; temperature range –20 – +50°C)) was fitted to the right arms of 12 subjects (GPSG). The data was recorded every 5 seconds, starting from the beach at the beginning of the race and finishing at the same place at the end. An AVM-40 (Kestrel 4000) anemometer was used to monitor wind speed, which varied from 10 to 14 $m \cdot s^{-1}$.

Statistical analysis

Initially, the Statistical Package for Social Sciences (SPSS) v. 14.0 programme was used for a normality test and homogeneity of variance. We then analysed the descriptive statistics and, finally, the Pearson's correlation coefficient was used to estimate the relationship between the anthropometric variables and the competition result.

RESULTS

Table 1 shows the anthropometric data for the professional competitors.

Table1. Descriptive data and somatotype characteristics for professional windsurfers

Professional (*n=15*)		
Dimension	**Mean±SD**	**Range**
Age (year)	25.4±3.9	20–33
Body mass Index (kg)	24.4±0.9	22.6–26.5
Height (cm)	184.6±6.4	172–194
Weight (kg)	83.1±5.3	73.3–92.6
Humerus width (cm)	7.63±0.32	7–8.4
Femur width (cm)	10.32±0.43	9.3–10.9
Upper arm girth (cm)[a]	32.93±1.16	30.2–35.4
Biceps girth (cm)[b]	35.17±1.29	32.5–37.3
Thigh girth (cm)	56.81±3.09	52.1–63
Calf girth (cm)	38.41±2.04	35.4–42
Pectoral skinfold (mm)	5.72±1.02	4–8
Triceps skinfold (mm)	7.67±2.06	5.8–13.4
Subscapular skinfold (mm)	9.69±1.22	8–12.8
Biceps skinfold (mm)	4.04±0.72	3–5.8
Iliac crest skinfold (mm)	12.47±2.53	9–16.8
Supraspinale skinfold (mm)	8.31±2.04	5.4–13
Abdominal skinfold (mm)	11.47±2.42	7.6–16.6
Front thigh skinfold (mm)	11.28±2.73	7.2–17.2
Medial calf skinfold (mm)	7.6±1.67	5.6–11.4
Muscle mass (kg)	35.5±1.8	32.4–38.9
Fat mass (kg)	8.9±1.8	6.4–12.6
Bone mass (kg)	14.1±1.5	11.2–17.3
Arm span (m)	1.9±0.1	1.7–2.1
Endomorphy	2.34±0.45	1.7–3.27
Mesomorphy	5.01±0.87	3.63–6.82
Ectomorphy	2.4±0.63	0.95–3.61

[a] *Midway between acromiom and olecranon, arm relaxed*
[b] *Maximum girth of the tensed upper arm (maximum flexed).*

Figure 2 shows that average muscle mass is 42.7% (35.5±1.8 kg), fat mass 10.7% (8.9±1.8 kg), bone mass 16.9% (14.1±1.5 kg) and residual mass 29.6% (24.6±1.9 kg) of body composition.

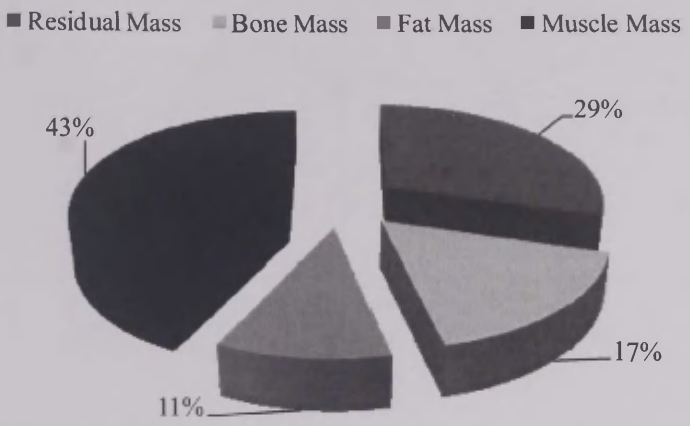


Figure 2. Body composition of professional windsurfers as a percentage.

The anthropometric profile of professional windsurfers competing in the Formula Windsurfing class is 2.3±0.4 endomorphy, 5±0.8 mesomorphy and 2.4±0.6 ectomorphy. The graphic professional somatotype for windsurfers is closer to meso-ectomorphy than to ectomorphy. Figure 3 shows the somatochart displaying the point of inflection of said values.

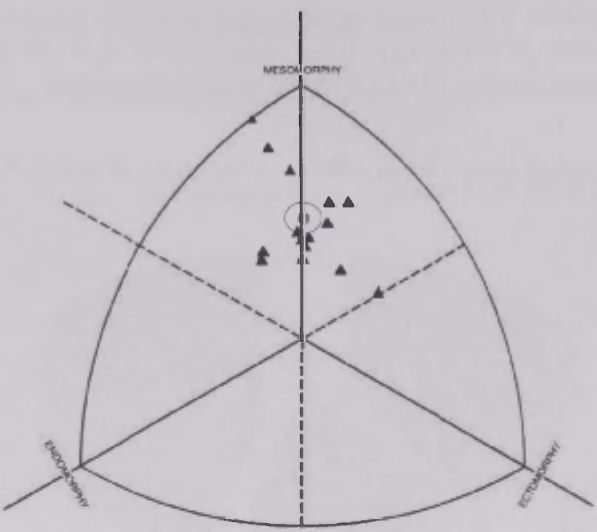
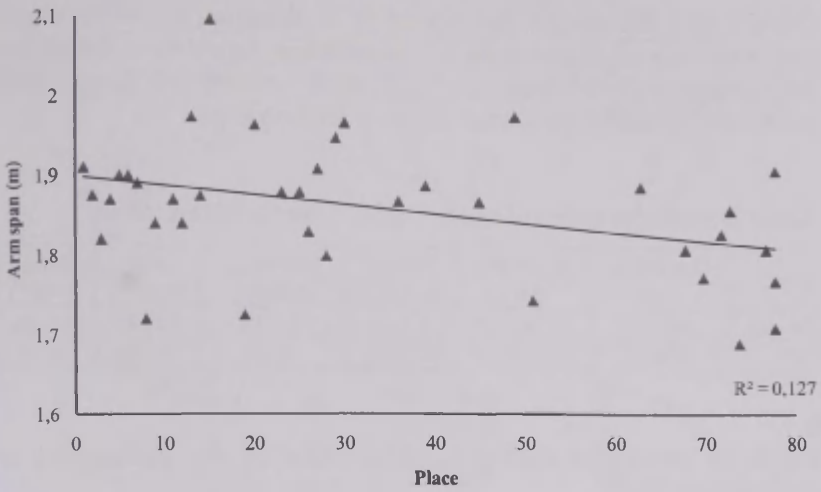
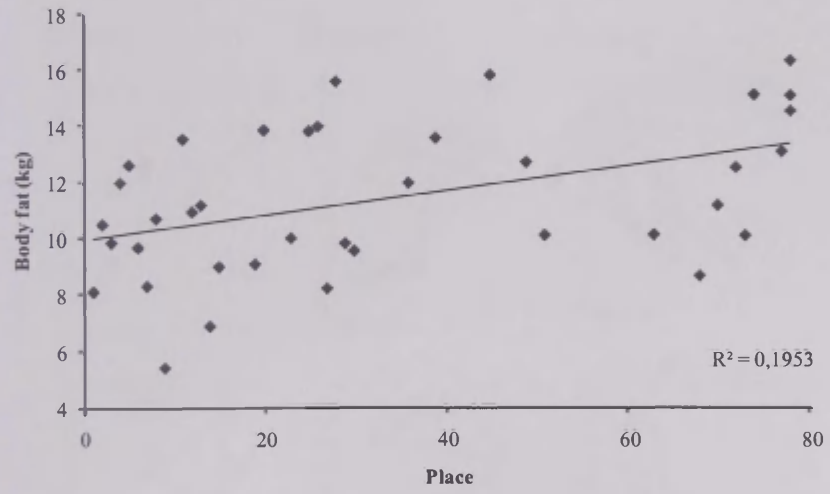


Figure 3. Distribution of somatotypes of windsurfers and mean somatotype of professional windsurfers. The circle around mean (●) represents the somatotype attitudinal distance from the mean value (SAM).

Of all the anthropometric data, only arm span and body fat gave significant correlations with the place obtained in the final classification ($p \leq 0.02$ and $p \leq 0.005$ respectively).





Figures 4 and 5. Relationship between arm span and fat mass and the final classification obtained in the competition.

Table 2 lists the means corresponding to duration, distance, speed, maximum speed, heart rate and maximum heart rate, based on information received from the GPS device during the second heat valid for the final classification of the championships.

Table 2. Variables gathered by the Global Position System device.

n=12	**Duration (s)**	**Distance (m)**	**Speed ($km \cdot h^{-1}$)**	**$Speed_{max}$ ($km \cdot h^{-1}$)**	**HR ($b \cdot m^{-1}$)**	**HR_{max} ($b \cdot m^{-1}$)**
Mean	2049.30	12784.77	11.84	34.32	127.62	180.46
SD	989.68	5522.19	2.38	3.86	13.73	26.92

Figure 6 shows the different routes taken by the competitors to complete the heat.

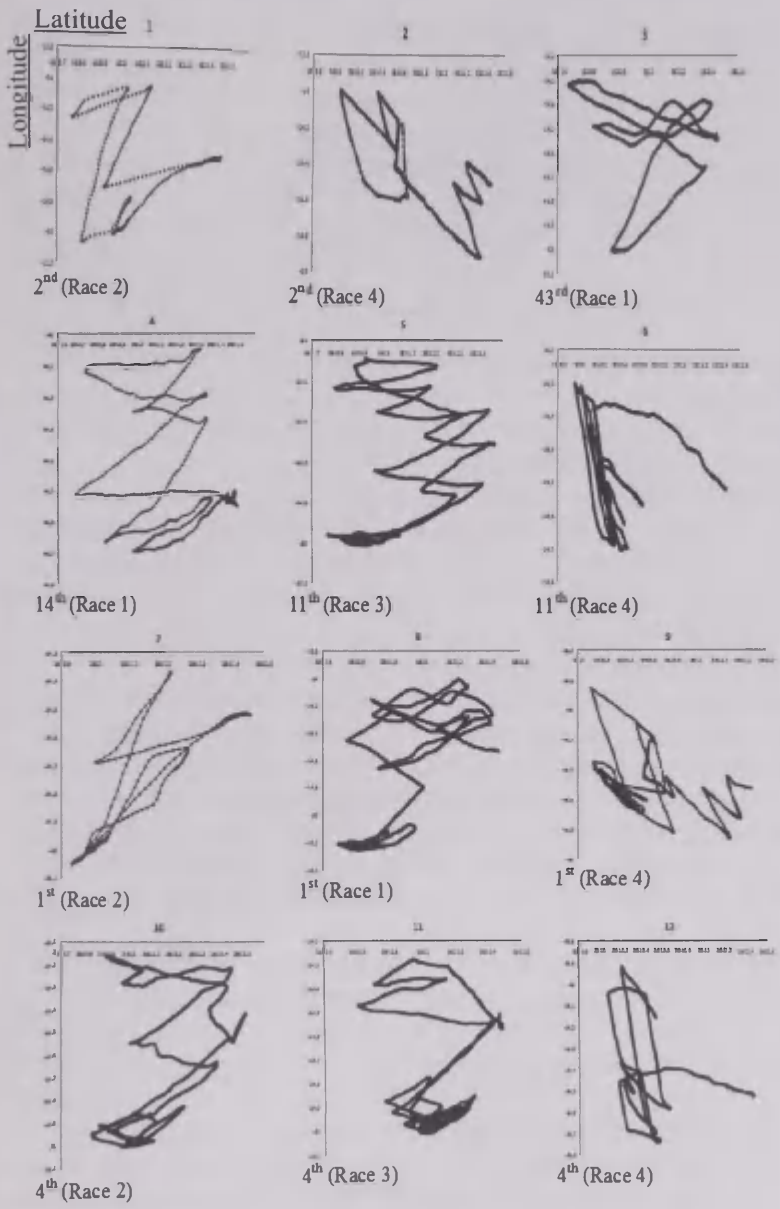


Figure 6. Route taken by each participant for the same heat. (Final classification and race).

DISCUSSION

Literature describing somatotype according to different sport modalities exist [10], even within the same sport, based on changes in technology and regulations experienced over time. Very little research is available, however for windsurfing. Porcella et al. [17] evaluated 79 windsurfers in the World Championships and pre-Olympic races celebrated in 1983 and 1986 in Italy, and found out that the mean somatotype components of the subjects who performed better was 2.57 – 2.68 – 2.97 showing slight domination of ectomorphy. In our study, however, both the professionals and amateurs showed a clear mesomorphy dominance over the other two components. The professionals in our study were also taller, heavier and had bigger arm and calf girths than those in the 1992 study.

It is not immediately obvious why these significant changes have occurred. Since 2006, there have been significant changes in the characteristics of board, with the development of a larger, more rigid table needing greater muscularity to sail it successfully (The Mistral One Design used until the 2004 Athens Olympic games was superceded by the Neilpryde RS:X for the Beijing Olympics). However, these changes alone cannot explain the differences in height and muscularity observed since 1992 as they are far are too recent. Professional windsurfers (and indeed all elite athletes) take far longer than a year to significantly change their group morphological profile.

What is more likely is that the changes seen in professional windsurfers parallel increases in height and muscularity in many strength sports over the past fifteen years, and it is clear that strength is a significant factor in windsurfing success.

Dyson et al. [9], discovered significant differences ($p<0.001$) between upper muscular group and lower muscular group use when they carried out a research over levels of muscular activity in Trapezius, Carpi flexors, Biceps brachii, gluteals and tibials, finding greater muscular participation of the upper muscular group, particularly isometrically. Campillo et al. [2], observed that much of the pain and injury seen in this sport was concentrated in the forearms and that this pain could be related to arm span, subjects with greater arm span being less likely to suffer pain. In our study we found the professional group presented a larger mean arm span than the amateur group (5.3%; $p<0.05$), but we did not conduct any comparison of pain experienced by the two groups so cannot comment on that aspect.

However, in our study we did not find significant correlations between the amount of muscle mass and the results of the competition, the same being true of body mass index and height. Nevertheless, we did observe significant correlations between the final classification and a larger arm span, something that should be taken into account when finding new talent. The same can be said for lesser fat mass. It also appears to be true that arm span could also be related to certain injuries suffered by windsurfers. Campillo et al. [2] observed that most pain caused by this kind of sport is felt in the forearm and that said pain could be related to arm span, as subjects with greater arm span usually have less problems and, on the other hand, said problems can be minimised by using a thinner boom.

With regard to the heart rate values, our results are similar to other studies of the Olympic class (145 and 173 $b \cdot m^{-1}$) [9]. It should be pointed out that the range of the Formula class is slightly greater (128 and 180 $b \cdot m^{-1}$). In the same way, Allen and Loke [1] saw that, with a wind speed of 3–5 $m \cdot s^{-1}$, mean heart rate during competition was 167 $b \cdot m^{-1}$ and with strong winds (12–15 $m \cdot s^{-1}$) mean HR was 154 $b \cdot m^{-1}$ in the Olympic class. Perhaps the reason Formula class has lower heart rate values is due to the structural differences of the materials used for each discipline. Vogiatzis et al. [20] state that the most important factor for energy demand during windsurfing is the pumping action and perhaps Formula windsurfing demands less pumping because the larger sail allows more advantage to be taken of gusts of wind. In addition, Castagna et al. [6] considered that Olympic windsurfing was a physical task linked with a high aerobic level demand, as is Formula windsurfing, although with slightly lower values.

The information provided by GPS devices can be of considerable help in acquiring a better understanding of the competitive reality of sports covering long distances. For example, they have been used for cross-country skiing [12], orienteering races [11] and mountain biking [3, 16].

With our results, based on GPS information, we observed great variability in the distances covered 12784.77±5522.19 m, and consequently in the time taken to complete the races 2049.3±989.68 s. This may be due to the different ways of approaching the races, as can be seen in Figure 5. These are related with the direction of the wind and the influence it has on the criteria of the judging committee when setting the course. In addition, the competitors have their own ways of

taking advantage of the strength of the wind and trying to optimise this leads to significant differences when dealing with the course set. With regards to speed (11.84±2.38 $km \cdot h^{-1}$) and maximum speed (34.32±3.86 $km \cdot h^{-1}$), we observed that they were presented in a quite homogenous fashion.

CONCLUSIONS

It is of considerable value to identify the current anthropometric profile of elite windsurfers, as this knowledge enables sport scientists and coaches to better match morphology with the performance required for success. This will assist not only in initial selection for the sport, but also in the design of training programmes which further develop that morphology, where possible, in the pursuit of improved performance.

It is probable that the need for environments with strong winds to hold Formula windsurfing championships and/or the structural difference lead to heart rates being somewhat lower than those observed for other windsurfing classes.

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