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Skeletal Muscle Deoxygenation in 11-13-year-old Children Swimmers During Arm and Leg Ergometry

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ABSTRACT

Background: This study extends the current knowledge on muscle deoxygenation during arm and leg ergometry in preadolescent swimmers. We aimed to compare the deoxygenation of legs and arms muscles during maximal incremental legs and arms exercises on the cycle ergometer (CE) and arm crank ergometer (ACE) in preadolescent swimmers.

Methods: Thirteen preadolescent swimmers (aged 12 ± 1 years) were enrolled in this study. They performed two maximal incremental legs and arms exercises to exhaustion on CE and on ACE. During both exercises, muscles oxygen saturation values (the changes of deoxygenated haemoglobin (Δ[HHb]) and [HHb] thresholds ([HHb] thresholds) of Biceps femoris, Vastus lateralis, Rectus femoris, Triceps brachii, Infraspinatus and Biceps brachii muscles were recorded using the near-infrared spectroscopy method (Moxy oxygen monitor).

Results: During maximal incremental legs and arms exercises on CE and ACE Δ[HHb] and [HHb] thresholds did not differ significantly between legs and arms exercises ($p>0.05$) and between separate muscles ($p>0.05$) as well.

Conclusion: Deoxygenation of legs and arms muscles was similar during incremental exercises on CE and ACE in preadolescent swimmers.

Keywords: muscles oxygenation, NIRS, upper and lower body exercise, graded exercise test

INTRODUCTION

It is known, that the demand for O_2 in the working skeletal muscles increases during incremental exercise, so the ability of the athlete's body to increase the amount of O_2 supplied to the skeletal muscles quickly and to activate the extraction of O_2 from the haemoglobin in the blood determines his level of physical fitness (Undebakke et al., 2019; Skattebo et al., 2020; Mazaheri et al., 2021).

Skeletal muscle deoxygenation during exercise can be measured by using a non-invasive method - near-infrared spectroscopy (NIRS) (Perrey & Ferrari, 2018). By measuring changes in O_2-saturated haemoglobin (O_2Hb) and myoglobin (mHb) this method allows to measure the O_2 supply and consumption ratio (Miranda-Fuentes et al., 2021). This ratio reflects skeletal muscle O_2 saturation (SmO_2) (Born et al., 2016).

In various studies, muscle deoxygenation in athletes is tested by applying incremental increasing workloads on different ergometers (Sousa et al., 2017; Furness et al., 2019; Bagiran et al., 2019). Most studies have shown, that the oxidative capacity of arm muscles is lower and lower muscle oxygen uptake rates are achieved during upper body exercises (Undebakke et al., 2019). It is known, that upper-body exercise involves the work of smaller muscle mass and puts less strain on the cardiovascular system than in lower body exercises (Undebakke et al., 2019; Skattebo et al., 2020; Saacks, 2020). Yet, athletes who train the whole body muscles at the same time (e.g., swimmers, rowers, skiers, etc.), show similar legs and arms muscles saturation values while performing legs and arms exercises (Jones & Cooper, 2016; Ørtenblad et al., 2018; Hansen et al., 2021).

However, the very limited research field on young swimmers (Jürimäe et al., 2007) especially in legs and arms deoxygenation, caused us to rely on our hypothesis on adult swimmers and other athletes who train the whole body muscles at the same time (Jones & Cooper, 2016; Ørtenblad et al., 2018). So according to studies with adult swimmers and other athletes, we hypothesised that deoxygenation of legs and arms muscles in young swimmers, who train whole body muscles (though preadolescent swimmers do not have sufficient physical and muscular strength and fully developed muscle mass in arms and legs (Costa et al., 2021), would be similar during maximal incremental legs and arms exercises on a cycle ergometer (CE) and arm crank ergometer (ACE). Therefore, the current study aimed to compare the deoxygenation of legs and arms muscles during maximal incremental legs and arms exercises on CE and ACE in preadolescent swimmers.

METHODS

Participants

Thirteen healthy swimmers volunteered to participate in this study. The inclusion criteria were as follows: (i) aged 11-13 years; (ii) attended regular training sessions four-five times per week; (iii) regularly participating in swimming competitions for the last two years; (iv) having no upper or lower limb injuries or other injuries in the last six months; (v) not suffering from severe chronic and acute diseases. The physical characteristics of the participants and the maximum power output reached during incremental leg and arm exercises on the cycle ergometer (CE) and arm crank ergometer (ACE) are presented in Table 1.

Table 1. **Physical characteristics of the participants in the study and maximum power output during legs and arms exercises on CE and ACE.**

Number of participants	13
Age, yr	12.0 ± 1.0
Height, cm	160.0 ± 7.6
Mass, kg	44.4 ± 10.5
Body mass index, kg/m^2	17.2 ± 2.8
Body fat, %	14.4 ± 7.2
Maximum power output during legs exercise on CE, W	180.9 ± 27.0
Maximum power output during arms exercise on ACE, W	84.8 ± 23.2

Note: Values are expressed as the mean ± SD.

Incremental exercises

Participants performed two maximal incremental legs and arms exercises in random order, with at least a 72-hour break between them. The incremental leg exercise was completed on a CE (Lode Corival, Groningen, Netherlands). The initial workload was 40 W for four minutes and after that, it was increased by 25 W every minute until exhaustion. The pedalling cadence was 70 revolutions per minute (rpm). The exercise was terminated when the participant was not able to keep the required pedalling rate. Immediately after the exercise, participants rested in a supine position for five minutes. Skeletal muscle deoxygenation was recorded throughout the exercise.

The incremental arms exercise was completed on an ACE (Lode Angio, Groningen, Netherlands). The initial workload was 10 W for four minutes and after that it was increased by 10 W every minute until exhaustion. The pedalling cadence was 70 revolutions per minute (rpm). The exercise was terminated when the participant was not able to keep the required pedalling rate. Immediately after the exercise, participants rested in a supine position for five minutes. Skeletal muscle deoxygenation was recorded throughout the exercise.

Muscle deoxygenation measurements

Skeletal muscle deoxygenation of the participants was measured during maximal incremental legs and arms exercises on CE and ACE using the near-infrared spectroscopy method (NIRS) and the analyser “IDIAG MOXY” (Contains FCC ID: O6R3067, Minnesota, USA). During both exercises, three devices were used on three different muscles. During leg exercise on CE muscle deoxygenation measuring devices were placed on the participants’ leg muscles: Biceps femoris (BF), Vastus lateralis (VL) and Rectus femoris (RF) muscles. During arms exercise on ACE muscle deoxygenation measuring devices were placed on the participants' arm muscles: Triceps brachii (TB), Infraspinatus (IF) and Biceps brachii (BB) muscles. The devices were fixed (glued) on the middle of the muscles' heads.

The NIRS method detects reflected light as a consequence of the amount of light absorbed by the tissue and determines the amount of oxygenation in the tissue. Muscle oxygenation was recorded every two sec, and averages of the muscle oxygenation index values in 15 sec intervals were used for index analysis.

Muscle oxygen saturation (SmO_2), expressed as a percentage and total haemoglobin ([tHb]) were recorded using the NIRS method. The amount of deoxygenated hemoglobin ([HHb]) was calculated from the obtained indicators, according to the formula:

$[HHb] = [tHb]/100*(100-SmO_2)$

From the [HHb] indicator calculated according to the formula, the minimum and maximum values during maximal incremental legs and arms exercises on CE and ACE were taken and the change between them was calculated, the obtained change was expressed as a percentage (Δ[HHb], %). The thresholds for the change of the [HHb] indicator were determined from the relationship between [HHb] and power using the computer program "Microcal Origin". The points when the [HHb] index, during maximal incremental legs and arms exercises on CE and ACE started to increase more rapidly or after a rapid increase its growth stopped were considered as ([HHb] threshold. Then the relative [HHb] thresholds expressed as percentage peak power reached during maximal incremental legs and arms exercises on CE and ACE were calculated by the formula:

[HHb] threshold (%) from max power output = ([HHb] threshold (W) x 100) / W max

Study design

Research was carried out at Lithuanian Sports University and all procedures were approved by the Bioethics Committee of the Lithuanian Sports University (No. (M)-2022-527). To attain a stable level of performance, participants attended in first familiarisation session. 2 days before the experiment, participants were introduced to the experimental procedures and performed 5 min low-intensity exercises on the CE and ACE. Written informed consent was obtained from all participants after an explanation of all details of the experimental procedures and the associated discomforts and risks. An individual testing protocol was created for each participant. On experiment day, participants performed two maximal incremental legs and arms exercises in random order on CE and ACE, with at least a 72-hour break between them.

Statistical analysis

All values are expressed as the mean and standard deviation (± *SD*). After analysis of normality (Shapiro-Wilk test) of the data, two-way analysis of variance (ANOVA) for dependent samples (test × muscle) was used to compare the values and to analyse significant main effects from the two different maximal incremental legs and arms exercises on CE and ACE and between separate muscles. Differences between variables were considered statistically significant when $p<0.05$. All calculations were performed using the statistical analysis package SPSS 28.0 and Microsoft Excel 2016 programs.

RESULTS

Participants performed two maximal incremental legs and arms exercises on a cycle ergometer (CE) and arm crank ergometer (ACE). During both exercises, muscle oxygen saturation values (the changes of deoxygenated haemoglobin (Δ[HHb]) and [HHb] thresholds ([HHb] thresholds) of Biceps femoris, Vastus lateralis, Rectus femoris, Triceps brachii, Infraspinatus and Biceps brachii muscles were recorded using the near-infrared spectroscopy method (Moxy oxygen monitor).

The Δ[HHb] in legs and arms muscles of preadolescent swimmers during maximal incremental legs and arms exercises on CE and ACE did not differ significantly between exercises ($p>0.05$) (Table 2) and between separate muscles ($p>0.05$) (Table 3).

Table 2. **The changes of deoxygenated haemoglobin in legs and arms of preadolescent swimmers during maximal incremental legs and arms exercises on CE and ACE.**

Exercise	Δ [HHb], %	p	Diff. %
Legs	246.0 ± 36.6	p>0.05	13.2
Arms	213.6 ± 45.5		

Note: Legs - maximal incremental legs exercise on CE; Arms - maximal incremental arms exercise on ACE.

Table 3. **The changes of deoxygenated haemoglobin in separate legs and arms muscles of preadolescent swimmers during maximal incremental legs and arms exercises on CE and ACE.**

Exercise	Muscle	Δ [HHb], %	p
Legs	BF	253.8 ± 149.7	p>0.05
	VL	206.1 ± 36.3	
	RF	278.1 ± 98.3	
Arms	TB	203.9 ± 60.8	
	IF	263.2 ± 144.1	
	BB	173.7 ± 25.5	

Note: BF - Biceps femoris m.; VL - Vastus lateralis m.; RF - Rectus femoris m.; TB - Triceps brachii m.; IF - Infraspinatus m.; BB - Biceps brachii m.

The [HHb] threshold in legs and arms muscles of preadolescent swimmers did not differ significantly ($p>0.05$) between exercises (Table 4) during maximal incremental legs and arms exercise on CE and ACE. However, the difference between the maximal power output of legs and arms exercises on CE and ACE was 53.1 % (Table 1).

Table 4. **The thresholds of deoxygenated haemoglobin in legs and arms of preadolescent swimmers during maximal incremental legs and arms exercises on CE and ACE.**

Exercise	[HHb] threshold, % from max power output	p	Diff. %
Legs	84.6 ± 19.9	p>0.05	0.1
Arms	84.5 ± 29.8		

Note: Legs - maximal incremental legs exercise on CE; Arms - maximal incremental arms exercise on ACE.

The [HHb] threshold (% from max power output) in separate legs and arms muscles of preadolescent swimmers did not differ significantly ($p>0.05$) (Table 5) during maximal incremental legs and arms exercise on CE and ACE.

Table 5. **The thresholds (% from max power output) of deoxygenated haemoglobin in separate legs and arms muscles of preadolescent swimmers during maximal incremental legs and arms exercises on CE and ACE.**

Muscle	[HHb] threshold, % from max power output	p
BF	85.7 ± 19.7	p>0.05
VL	83.2 ± 23.4	
RF	84.8 ± 16.5	
TB	76.6 ± 19.3	
IF	77.4 ± 35.5	
BB	99.3 ± 34.6	

Note: BF - Biceps femoris m.; VL - Vastus lateralis m.; RF - Rectus femoris m.; TB - Triceps brachii m.; IF - Infraspinatus m.; BB - Biceps brachii m.

DISCUSSION

The purpose of this study was to compare the deoxygenation of legs and arms muscles during maximal incremental legs and arms exercises on a cycle ergometer (CE) and arm crank ergometer (ACE) in preadolescent swimmers. The main finding was that Δ [HHb], [HHb] thresholds did not differ significantly between legs and arms and between separate muscles during maximal incremental legs and arms exercises on CE and ACE in preadolescent swimmers. While we have hypothesised that deoxygenation of legs and arms muscles in young swimmers, who train whole body muscles, would be similar during maximal incremental legs and arms exercises on CE and ACE, our results support this hypothesis.

Some studies' results were similar to this study's results. Jones & Cooper (2016) found no significant difference in the changes in tissue haemoglobin saturation index between the Vastus lateralis (VL) and Latissimus dorsi muscles in club-level swimmers after a maximum 200 m freestyle swim exercise when triathletes experienced a significantly greater drop in the tissue haemoglobin saturation index in the upper body compared with the lower body. These data suggest that club-level swimmers use both the upper and lower body muscles to a similar extent during a maximal 200 m swim effort. Club-level triathletes, however, predominantly use the upper body for propulsion during the same exercise.

Also, some studies showed no significant differences between upper and lower body exercise performances and sex in female and male cross-country skiers (Hansen et al., 2021), or that metabolic profiles (mitochondrial volume and the average number of capillaries per fibre) in the well-trained arms (Triceps branchii (TB) and legs (VL) muscles of the elite cross-country skiers, were similar (Ørtenblad et al., 2018).

Although some previous studies reported that peak oxygen uptake during upper body exercise was approximately 70 % to 75 % of that attained during leg exercise (Bhambhani et al., 1998; Bhambhani, 2004; Undebakke et al., 2019; Lanigan, 2022). Studies show, that arm muscles generally release less oxygen than leg muscles and have a lower oxidative capacity than legs (Koppo et al., 2002; Calbet et al., 2015), as the breaking point of muscle oxygenation (accelerated decrease in the muscle oxygenation index (as changes in O_2Hb and HHb) occurred earlier in arm muscle (Biceps branchii (BB) compared with leg muscle (VL) during rowing exercise (Zhang et al., 2010).

Saacks (2020) found that oxygen saturation deficit was greater in lower body muscle than in upper body muscle, as muscle oxygen saturation was significantly lower in VL than in BB muscles during a rowing exercise. Also, Lanigan (2022) reported, that Δ[HHb] was greater in gastrocnemius medialis (GM) muscle and VL than BB muscle ($p<0.05$) after rowing exercise. Another study by Meyer and colleagues (2021) found, that lower limb muscles have 42% bigger muscle oxidative capacity than the upper limb when swimmers, rowers and runners performed leg extension exercises for VL and arm flexion exercises for BB muscle.

However, some studies showed greater Δ[HHb] in arm muscles than in leg muscles after a maximal repeated sprint test to exhaustion on a CE and ACE (Willis et al., 2019). Another similar study showed that total haemoglobin concentration was 65 % higher in arms versus legs, suggesting that arms had a greater blood perfusion capacity than legs (Willis et al., 2020).

Usually, bigger muscle deoxygenation values were measured during lower body exercises when larger muscle mass was activated. Lower limb muscles tend to have a higher oxidative capacity than the upper limb muscles (Bhambhani et al., 1998; Zhang et al., 2010; Undebakke et al., 2019). The results of some studies suggest that the muscles of the arms are more sensitive to oxygen delivery than the muscles of the legs, likely due to their smaller muscle mass requiring higher oxygen demand, and the arms are known to have generally lower tissue oxygen extraction and perfusion but higher relative blood flow than the legs (Calbet et al., 2015).

However, athletes, who train the upper and lower body muscles the same (e.g. swimmers, rowers, skiers, etc.), have more similar decrease in oxygen saturation in arms and legs muscles while performing upper and lower body exercises (Jones & Cooper, 2016; Ørtenblad et al., 2018). It could be assumed, that the reasons for similar [HHb] indicator values in the preadolescent swimmers' legs and arms muscles in our study were due to the similar upper and lower body training during swimming.

Research shows that athletes in this age group (about 10-13 years) belong to the period of puberty (Wood et al., 2019) and their values of aerobic capacity indicators are lower when performing progressively increasing physical load tests, compared to adults. This can be attributed to lower anaerobic capacity in children and adolescents (Armstrong & Welsman, 2017; Armstrong & Welsman, 2019; Armstrong & Welsman, 2020), young athletes lower physical and muscular strength and fully developed muscle mass (Costa et al., 2021). Although research filed on young swimmers (Jürimäe et al., 2007) or other young athletes analysing leg and arm muscle oxygen saturation is very limited and more focused on leg muscle oxygenation responses (Shirai et al., 2023; Ušaj, et al., 2019) and not comparing legs and arms muscles.

The most important practical significance of our study has been preadolescent swimmers as participants and the limited number of similar studies. Still, our study's limiting factors could be the relatively small number of participants, their young age and, as a result, the little swimming training experience of the participants. Further research development opportunities would include the mechanisms of blood flow regulation and oxygen transport in arm and leg muscles during upper and lower body exercises with a larger number of subjects and elder subjects with more experience in swimming training.

CONCLUSION

Deoxygenation of legs and arms muscles was similar during incremental exercises on CE and ACE in preadolescent swimmers.

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