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Institute of Sport Sciences and Physiotherapy, Faculty of Medicine, University of Tartu, Tartu, Estonia

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PAPER II
Arend, M., Kivastik, J. and Mäestu, J. Maximal Inspiratory Pressure is influenced by intensity of the warm-up protocol. Respir Physiol Neurobiol. 2016; 230: 11−15.

PAPER III
Arend, M., Mäestu, J., Kivastik, J, and Talts J. The effect of inspiratory muscle warm-up on VO_2 kinetics during submaximal rowing. Sports (Basel). 2021; 9: 42.

In Papers I, II and III Mati Arend had primary responsibility for protocol development, enrolment of the participants, performing measurements, data analysis, and writing the manuscripts.

ABBREVIATIONS

BMI	body mass index
VO_{2max}	maximal oxygen consumption
VO_{2max}/kg	maximal oxygen consumption per kg of body mass
Pa_{max}	maximal aerobic power
MIP	maximal inspiratory mouth pressure
IM	inspiratory muscles
IMT	inspiratory muscle training
La pre	lactate concentration before submaximal performance test
La post	lactate concentration after submaximal performance test
V_E	minute ventilation
HR	heart rate
BF	breathing frequency
FVC	forced vital capacity
FEV_1	forced expiratory volume in 1 s
PEF	peak expiratory flow
PIF	peak inspiratory flow
RER	respiratory exchange ratio

1. INTRODUCTION

In sport, technological and scientific support for athletes and coaches provide a range of options in search of improving physical performance and recovery. This has led to additional activities and strategies to well-known training methods such as resistance and cardiovascular training. One of the proposed additional training methods that has received attention for endurance athletes is the specific respiratory muscle training and warm-up prior to highly intensive activities (competitions).

In relative resting conditions the diaphragm and accessory inspiratory muscles have minimal metabolic requirements. But these muscles need to be very active in exercise conditions, receiving as much as 15% of total cardiac output during heavy exercise to meet the physiological and metabolic demands of the activity (Harms et al., 1998). The respiratory system consists of airways, lungs, blood vessels, ribcage, diaphragm and neck muscles. This system is responsible for delivering oxygen to the blood and removal of carbon dioxide from the blood to the lungs (McKenzie, 2012). Therefore, the respiratory system plays a key role in endurance athlete performance.

Previously it was thought that respiratory system is not a limiting factor to endurance performance, but different research has shown that inspiratory muscle (IM) might fatigue and this further might induce decrease in their performance which further might contribute with a negative effect on overall athletic performance, which can occur after prolonged submaximal, and even following after short-term maximal exercise (Inbar et al., 2000; Johnson et al., 1993).

Rowing is a highly demanding sport for musculoskeletal, cardiovascular, and respiratory system, involving more than 70% of the total muscle mass during the classical 2000m rowing race, while performing at the intensity of approximately 95–100% of maximal oxygen consumption (VO_{2max}). Furthermore, in rowing, the slumped position at the start of the rowing stroke might inhibit the ability of the diaphragm, as the main inspiratory muscle, to work efficiently. This indeed might lead to earlier fatigue of the inspiratory muscles. Therefore, a stronger and more efficient respiratory system might help to delay the fatigue of the respiratory muscles, maintain the limb blood flow for longer periods and enhance acute athletic performance of the athlete (Witt et al., 2007).

During rowing training and competitions different muscles and muscle groups are highly dependent on the oxygen availability and high demands on the performance of respiratory muscles might play a critical role. Maximal oxygen consumption and associated physiological variables are important factors for endurance athletes, including rowers, in terms of monitoring and testing performance. Coaches and scientists have been interested in training interventions to improve VO_2 kinetics and consequently the athletic performance. One possible approach in acute situation for improvement of VO_2 kinetics has been through different warm-up or priming exercises to influence VO_2 kinetics throughout the following task.

Inspiratory muscle training (IMT) during longer period has been studied extensively on athletes and non-athletes and the results of two systematic reviews and meta-analysis indicate positive results of IMT on performance (Illi et al., 2012; McConnell et al., 2004; Shei et al., 2018). However, less research focus has been on an acute inspiratory muscle warm-up prior to activity where only some individual research articles have been published (Barnes et al., 2021; Leicht et al., 2010; Lin et al., 2007; Tong and Fu, 2006; Volianitis et al., 2001) but for a systematic review there seems to be too little research to draw any final conclusions.

Therefore, the present dissertation aims to investigate the inspiratory muscle performance and the effect of IM warm-up on overall rowing performance or the physiological parameters which contribute to the rowing performance.

2. REVIEW OF THE LITERATURE

2.1 Inspiratory muscle fatigue and the basis for inspiratory muscle warm-up

The human diaphragm is a primary inspiratory muscle as it provides 75 % of ventilation and plays a key role in controlling the spine during postural control (Hodges et al., 2000; Polla et al., 2004). Diaphragm generates 70–90% of total inspiratory pressure during exercise and it has been shown that athletes have more advanced diaphragm muscles compared to regular (Hellyer et al., 2017). Even though the rowers have relatively cramped body position at the start of the rowing stroke which increases the intra-abdominal pressure by creating additional resistance to the movement of the ribcage, minute ventilation levels up to 270 L min^{-1} have been recorded during rowing and the average values of elite rowers reach 200–210 L min^{-1} (Mäestu et al., 2005). This crouched position at the beginning of the rowing stroke may be one additional factor for inspiratory muscle fatigue in rowers during high intensity rowing tests or during the competitions (Hamnegard et al., 1996; Johnson et al., 1993; Suzuki et al., 1991; Strongoli et al., 2010; Volianitis et al., 2020). Even though respiratory muscles have high aerobic capacities with a unique resilience to vasoconstriction making them naturally fatigue-resistant to low-moderate exercise intensities, they are susceptible to fatigue when exercising at intensities over 85% of VO_{2max} for prolonged periods of time (Dempsey et al., 2006; Johnson et al., 1993) or under the conditions of external respiratory loading (Welch et al., 2018). Therefore, a negative effect on athletic performance can occur (Inbar et al., 2000). Both human and experimental animal studies show that the fatigue of the diaphragmatic work is associated with a sympathetically mediated metaboreflex (de Bisschop et al., 2014; Geary et al., 2019; Harms et al., 2000; Sheel et al., 2001), which reduces blood flow to the locomotor muscles and may lead to fatigue (Wüthrich et al., 2015).

In a systematic review, IM training has been shown as an effective supplement to training for positive gains in athletic performance (Illi et al., 2012). Research carried out on rowers has shown increases in MIP, mean power and time trial results of 6-min all-out tests and 5000m tests. For example, Riganas et al. (2008) found significant changes in MIP but no positive changes in 2000m rowing performance after six weeks of IM training. In contrast, Volianitis et al. (2001) showed that after 11 weeks of IM training MIP was higher after incremental exercise test compared to baseline testing and 6-min all-out test time improved by 3.5 (+/–1.2) % and 5000m all-out test time was improved by 3.1(+/–0.8) %. Similarly, Griffits et al. (2007) showed that already four weeks of IM training induced about 2.7% increase in mean power and 2–5% decrease in heart rate during 6-min all-out test. Barnes et al. (2021) group suggested that IM warm-up might improve 3,200-m running performance by perceived changes in inspiratory muscle function and reduction in dyspnea. Interestingly, the systematic review from Illi et al. (2012) points out that half of the tests that reported exercise intensity (n=40) were performed below the threshold of 85% VO_{2max} which is considered the fatiguing point of respiratory muscles (Johnson et al., 1993). Therefore, more research performed at higher constant load (>85% VO_{2max}) might be needed to understand the potential IM warm-up effects or mechanisms on athletic performance.

In comparison to IM training, the effects of an acute bout of inspiratory muscle warm-up on athletic performance have received less attention in scientific research and the results so far are controversial. For example, Lin et al. (2007) have shown an improvement in badminton players' maximal footwork test, and decreased sensation of breathlessness from enhanced IM function after an acute bout of IM warm-up. Similarly, Brown et al. (2014) found significant improvement in maximal 100 m swimming performance after IM warm-up was added to the regular swimming warm-up. Johnson et al. (2014) analyzed 10km time-trial performance in male cyclists and concluded that adding IM warm-up to cycling warm-up programs did not significantly improve the 10km time-trial performance when compared to cycling warm-up alone. However, the experimental group who also used IM warm-up showed an 8% increase in IM strength after IM warm-up which was considered as significant ($p<0.05$).

Before competition prior exercise warm-up or a "priming exercise" is used by rowers to enhance neuromuscular and cardiorespiratory system and to prepare themselves for the upcoming race. However, it is not the intention of the rowers to perform a very intensive warm-up, as it may result in elevated lactate values at the start of the race, which might negatively affect the power development at the second half of the race (Volianitis et al., 2001A; Volianitis et al., 2001B). Therefore, the traditional warm-up might not be intensive enough to warm up the inspiratory muscles and the additional respiratory muscle-specific warm-up could be beneficial.

In rowing, the competitions can be characterized usually as one or two maximal all-out races per day. This further induces relatively high load on the respiratory system and raises a question of how long it could take for the respiratory muscles to recover from a single bout of exhaustive exercise; or whether fatigue of inspiratory muscles might induce the change (decrease) in overall performance. Kyroussis et al. (1996) investigated the effect of two minutes of maximal isocapnic ventilation on abdominal muscle fatigue, the twitch gastric pressures (elicited via magnetic stimulation of abdominal muscles) reduced significantly from baseline and remained lower 90 minutes following the ventilation bout. Therefore, acute inspiratory muscle loading as a "priming exercise" may improve rowing performance in high intensity exercise domain. It could be hypothesized that the use of constant intensity, where the overall work conditions are more controlled, might be more useful in this case to detect possible physiological changes caused by inspiratory muscle warm-up.

2.2 The intensity of the inspiratory muscle warm-up

Compared to IM training fewer studies have investigated effects of IM warm-up on maximal inspiratory pressure (MIP) and on athletic performance (Brown et al., 2014; Johnson et al., 2014; Lin et al., 2007; Tong and Fu, 2006; Volianitis et al., 2001A, B). There are few papers which have shown a good correlation between changes in MIP and changes in exercise performance following the IM warm-up (Barnes and Ludge, 2021; Griffiths and McConnell, 2007; Lomax et al., 2011). The applied intensity of IM warm-up in previous research has been relatively low: either 40% of MIP or 15% of MIP for sham (placebo) protocols with two sets of 30 inspirations in both cases. In contrast, moderate to high intensities have been used for whole body warm-up prior to regular sporting activities which have been related to better results in athletic performance (Zois et al., 2013; Zois et al., 2015). This results also in the shorter overall time needed for warming up before training or competition (Saez Saez de Villarreal et al., 2007). However, to our best knowledge less is known about the different intensities used for IM warm-up for priming up inspiratory muscles before high demanding exercise.

It can be concluded from the previous studies that the effect of inspiratory muscle warm-up on performance might be relatively small. However, in practical setting every little gain in performance that can be obtained using different methods might separate the winners and those who miss the podium. As maximal performance is influenced by several factors that can influence the result of the test (i.e., motivation to produce truly maximal effort, the use of maximal all-out tests might not be sensitive enough to detect possible changes in performance.

2.3 Fast and slow components of VO_2 kinetics

Since VO_{2max} and associated physiological variables are important factors in terms of endurance performance, coaches and scientists have been interested in testing and training interventions to measure or improve VO_2 kinetics. The characteristics of VO_2 kinetics help to understand the mechanisms controlling the O_2 consumption in humans during exercise (Adami et al., 2011). Traditionally, the dynamic VO_2 response to exercise has been categorized into three intensity domains: moderate (below the anaerobic threshold), heavy (above the anaerobic threshold), and severe (above the critical power until the VO_{2max}) (Sousa et al., 2014). During moderate intensity a steady-state VO_2 is reached in 2–3 minutes from the start of the exercise (Pringle et al., 2003). In the heavy intensity exercise, there is and additional delay in achieving the steady-state VO_2 (VO_2 slow component). Analyzing VO_2 kinetics by separating fast and slow components at the onset of exercise may give insight into the factors that regulate oxidative metabolism (Barker et al., 2010; Sousa et al., 2014).

Previous research has shown to affect the magnitude of VO_2 kinetics and prior exercise warm-up or a “priming exercise” to enhance neuromuscular and cardiorespiratory system is frequently used to increase the amplitude of the fast component and to reduce the amplitude of the slow component (Gerbino et al., 1996). It could be hypothesized that during the conditions in IM fatigue, changes in the parameters VO_2 kinetics could appear.

Higher amplitude of the fast component of VO_2 kinetics seems to be directly related to the best performances in the 400m front crawl swimming (Fernandes et al., 2009). Koppo et al. (2002) have shown that the time constant (τ) of the VO_2 fast component response to exercise was longer in arm cranking compared to lower limb activity. Therefore, slower VO_2 kinetics might be expected in rowing. However, the study of Roberts et al. (2005) indicated that pulmonary VO_2 kinetic responses to moderate and heavy intensity exercises during upright cycle and rowing ergometer exercises were similar.

During constant work rate the time constant of the VO_2 response to a transition from rest to exercise is usually faster in healthy, young athletes compared to non-specifically trained subjects (Jones and Burnley, 2005; Poole and Jones, 2012). Shorter time constant has been associated with improved exercise tolerance and performance in cycling, running and rowing (Burnley and Jones 2007; Ingham et al. 2007; Whipp et al., 2002). Some research has also indicated shorter time constant in athletes with higher VO_{2max} (Norris and Petersen, 1998; Powers et al., 1985), while others have not (Barstow et al., 2000; Pringle et al., 2003).

In rowing the competition intensity is in the high domain and previously used VO_{2max} assessment might not give us the necessary information about the ability of the rower. The studies that measure the VO_2 kinetics in rowers are yet few and the purpose of this study was to characterize the VO_2 kinetics during a near maximal rowing test with prior inspiratory muscle warm-up to mimic the competition conditions rowers usually have.

3. THE AIM OF THE STUDY

The overall purpose of the current thesis was to investigate the effect of specific inspiratory muscle warm up on different physiological and performance related variables of rowing ergometer performance.

Specific aims of the thesis were:

1. To compare the effect of 40% MIP intensity inspiratory muscle warm-up on submaximal rowing performance performed at 90% intensity of maximal aerobic power during submaximal rowing tests if traditional rowing warm-up or IM warm-up with additional traditional rowing warm-up is used (Paper I).
2. To compare the effect of 40% MIP intensity inspiratory muscle warm-up on lactate concentration and breathing values during submaximal rowing tests if traditional rowing warm-up or IM warm-up with additional traditional rowing warm-up is used (Paper I).
3. To investigate the effect of different intensities of inspiratory muscle warm-up to maximal inspiratory muscle strength (Paper II).
4. To compare the effect of IM warm-up on VO_2 kinetics during the slow component phase in submaximal rowing (Paper III).

4. METHODS

4.1 Sample size, subject characteristics and data collection

The current dissertation is combined of a one preliminary study (unpublished data) that investigated the effect of inspiratory muscle fatigue in rowing after different all-out tests, and of three different studies to better understand the physiological mechanisms behind inspiratory muscle warm-up and their potential effect on rowing performance. The overall schematic view of the study protocols is presented on Figure 1.

Table 1. Sample size and subject characteristics from Papers I, II and III that are included to the present thesis.

	Preliminary study (unpublished data) (National level male rowers)	**Paper I, III** (High level male rowers)	**Paper II** (Recreationally active males)
Sample size	12	10	10
Age (years)	20.0±2.9	23.1±3.8	26.4±4.1
Height (cm)	185.0±6.9	188.1±6.3	183.3±5.5
Weight (kg)	81.3±8.6	85.6±6.6	83.7±7.8

Study I and III were conducted on high level Estonian rowers and measured the effect of inspiratory muscle warm-up on submaximal rowing performance. In addition, the effect of IM warm-up on parameters of slow and fast components of VO_2 kinetics was studied (Table 1). Study II was conducted on recreationally active healthy males to measure the effect of different inspiratory muscle warm-up intensities to the maximal inspiratory mouth pressure. All study procedures were performed in accordance of the Helsinki Declaration and were approved by the Research Ethics Committee of the University of Tartu.

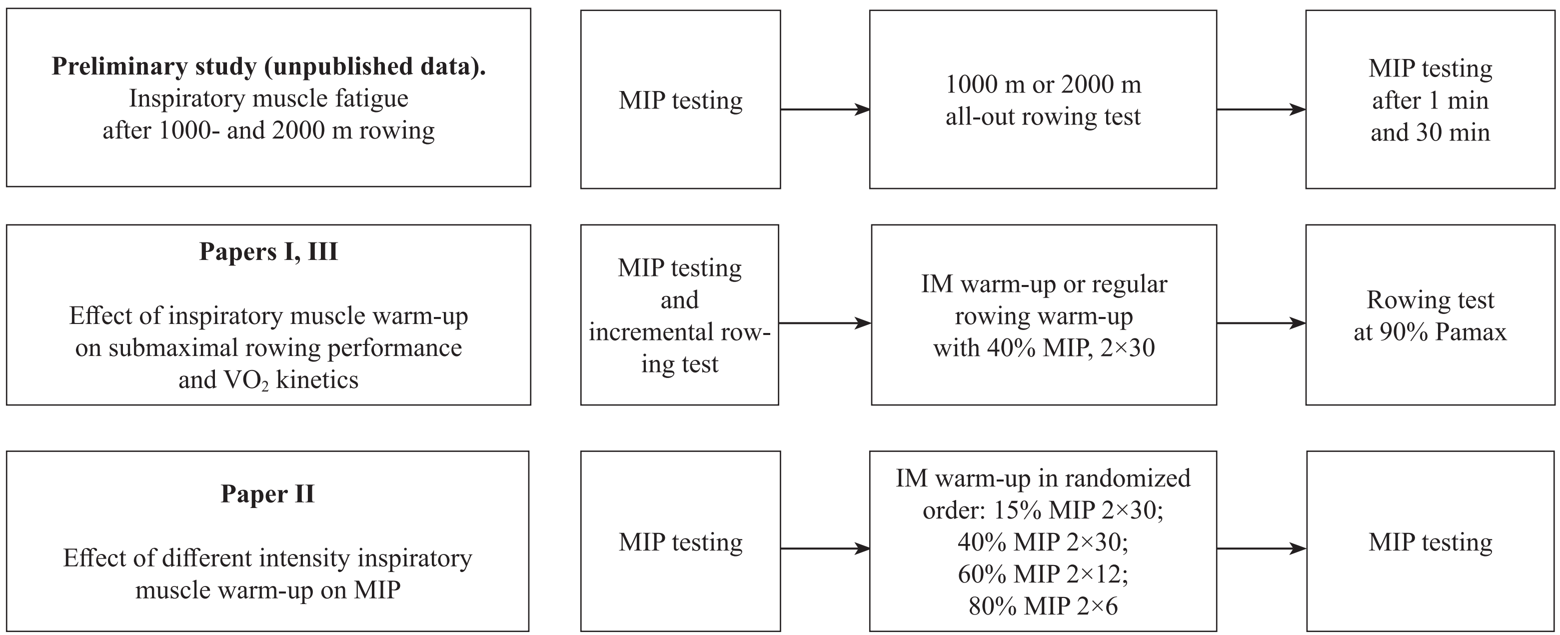

Figure 1. The descriptive overview of the study protocols. Pa_{max} – maximal aerobic power; IM – inspiratory muscle; MIP – maximal inspiratory mouth pressure.

4.2 Measurement of maximal inspiratory pressure (Paper I, II and III)

All subjects participated in the experiments with which they were not previously familiar and therefore, the familiarization sessions were carried out before all studies. MIP measurement was performed as a maximal isometric inspiratory maneuver from residual volume, and it was registered according to the present ATS/ERS statement on respiratory muscle testing (ATS/ERS, 2002) using a mouth pressure meter MicroRPM (Micro Medical, Kent, UK). All MIP measurements were done with the subject in a seated position looking straight ahead and wearing a nose clip. The subjects had to perform five to seven MIP tests to minimize the learning effect before starting the study. Verbal encouragement during MIP testing was given to assist the subjects in performing maximally.

After the familiarization process for MIP testing, a five-minute rest was provided, and baseline MIP measurement started again from residual volume. To obtain the highest MIP value, all subjects performed a minimum of three and a maximum of seven attempts to obtain three values with differences not higher than 5%. The highest value of three acceptable MIP results (maximal mean pressure the subject could hold for 1 s) was used to calculate the load for inspiratory muscle warm-up before every intervention. The rest intervals of 1min were allowed in-between MIP trials.

4.3 Incremental exercise testing (Paper I and III)

The incremental test was performed on the same day as MIP test, with approximately 5 minutes break to move to rowing ergometer after completing the MIP test. The incremental test protocol started with a 10-min individual low intensity warm-up on a rowing ergometer (Concept II, Morrisville, VT, USA). The resistance of the flywheel was set to number 5 for all the participants and was kept constant during the test. The first stage was set on 150 W and the increments were 50 W after every three minutes until exhaustion (Jürimäe et al., 1999). The test was completed if at least one of the following situations occurred: 1) there was a plateau in oxygen consumption value; 2) respiratory exchange ratio (RER) increased to a value of 1.1 or more or; 3) the subject could not maintain the given intensity for five consecutive strokes. During the test, maximal oxygen consumption (VO_{2max}), minute ventilation and RER were constantly measured using breath-by-breath method. Respiratory parameters were registered with a portable oxygen analyzer with facemask (Metamax 3B, Cortex GMBH, Leipzig, Germany). Individual maximal aerobic power (Pa_{max}) during the test was calculated according to the following formula (Kolle et al., 2010):

$$Pa_{max} = P1 + P2 \times T/180,$$

where P1 = power of the last fully completed stage, P2 = power increment (50 W in our test), T = duration of the final incomplete stage (in seconds).

After incremental test the subjects were further familiarized with the inspiratory muscle training device PowerBreathe® (IMT technologies Ltd, Birmingham, UK) to minimize the learning effect.

4.4 Submaximal intensity rowing test at 90% Pa_{max} intensity (Paper I and III)

During the studies I and III, submaximal 90% rowing test was carried out twice on the rowing ergometer in randomized design, to exclude the effect of testing order of the performance measurements. 90% Pa_{max} test was used with regular warm-up only (Test 1) or with regular warm-up followed by inspiratory muscle warm-up (Test 2). The resistance of the flywheel on the rowing ergometer was set to number 5 and was similar in both tests. During the 90% Pa_{max} test the subjects had to row at the predetermined intensity, but not longer than 20 min. The display of the rowing ergometer was covered so that the subjects could not see the covered distance or the exercise time. Before Test 1 subjects had to perform a standardized warm-up, which consisted of six minutes of rowing at 50% Pa_{max} and two minutes at 75% Pa_{max} intensity. After that the oxygen mask was put on and the 90% Pa_{max} test was performed. Before Test 2, all subjects had to perform the same standardized rowing warm-up and additionally, a specific inspiratory muscle warm-up with PowerBreathe® (2x30 inspirations at the intensity of 40% of MIP, with 2 min of rest between the sets) (Volianitis et al., 2001; Wilson et al., 2013). To maintain the needed level of inspiratory pressure, the PowerBreathe® device was connected to the manometer and the subject could see the pressure level on the screen.

During both performance tests, heart rate was monitored with a Polar sport-tester (Polar, Kemppele, Finland) and the respiratory parameters were registered with a portable oxygen analyzer using breath-by-breath method. The duration of the test, distance covered, heart rate, breathing frequency, VO_2, RER and minute ventilation were measured. Pre-exercise and post-exercise (on third and fifth minute) blood samples were collected from fingertip and analyzed for lactate concentration using the enzymatic method (Lange GMBH, Leipzig, Germany).

4.5 The use of different intensities of inspiratory warm-up (Paper II)

All subjects performed four inspiratory muscle warm-up protocols under similar conditions during the same time in the afternoon, in a randomized order. During all occasions, the subjects had to perform MIP testing first and then in randomized order carry out the IM warm-up with different intensities based on the progressive model of strength training (Kraemer et al., 2002). After familiarization with the testing procedures the subjects performed the maximal inspiratory pressure (MIP) testing and started with IM warm-up protocols in a randomized order, MIP was measured again after the warm-up. (Figure 3). Based on the MIP testing result, the subsequent individual load for different warm-up protocols was calculated. The MIP testing was conducted 5 minutes after the completion of the warm-up protocol, so each of the subject acted as his own control. Testing sessions were separated by a minimum of one week to minimize the training effect.

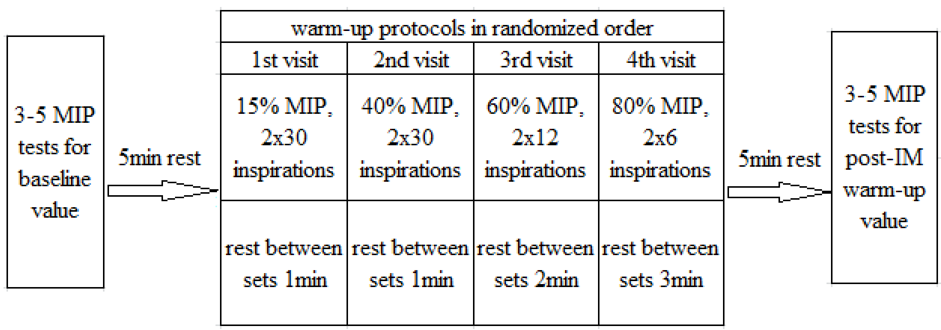

Figure 3. Overview of the different inspiratory muscle (IM) warm-up protocols. MIP – maximal inspiratory pressure.

A commercially available handheld inspiratory muscle training device (PowerBreathe® K1, PowerBreathe International Ltd, Warwickshire, UK) was used for the IM warm-up with the subject in a seated position. A nose clip was worn during the IM warm-up sessions to avoid nasal air leak. Subjects performed the warm-up protocols 5 minutes after completion of the MIP testing. Four different intensities (15%, 40%, 60% and 80% MIP) were used in a randomized order to avoid the effect of testing order. The same PowerBreathe® device was used for each warm-up session and the specific load was set up individually calculated from personal baseline MIP. Since the K1 series optimizes the resistance during the first two breaths and then incrementally applies it, we did not count the first two breaths during the protocols. During all IM warm-up protocols, breathing frequency was paced by the K1 device with an audible beep. Time interval between the inspirations was kept constant at 4.5 seconds. Subjects were asked to inhale as quickly and deeply as possible. During all warm-up protocols the performed load was also calculated by multiplying the number of repetitions with defined individual intensity of MIP.

4.6 VO2 Kinetics during Submaximal Rowing (Paper I and III)

When analyzing the VO_2 data in Paper I, we excluded the fast component of oxygen consumption and the average VO_2 values were calculated during slow component of oxygen consumption only.

During Study III, breath-by-breath VO_2 data were edited to reduce influence of outliers: each value was compared against the dataset consisting of the preceding and subsequent three data points; the value was excluded, if it was outside 4 SD from the average of this dataset. The remaining VO_2 data until 400 s of exercise were interpolated to 1 s intervals and then data points were averaged to 5-s intervals to further reduce noise (Kolkhorst et al., 2004).

A non-linear least-squares method was implemented in the MatLab Software (Math- works, Natick, MA, USA) to fit the VO_2 data with the model. To characterize the on- transient VO_2 kinetics, a double-exponential model was used, as follows:

$$\dot{V}_{O_2}(t) = \begin{cases} A_0 + A_1 \cdot \left(1 - e^{-(t-TD_1)/\tau_1}\right) & for \quad t < TD2 \\ A_0 + A_1 \cdot \left(1 - e^{-(t-TD_1)/\tau_1}\right) + A_2 \cdot \left(1 - e^{-(t-TD_2)/\tau_2}\right) & for \quad t \geq TD2 \end{cases}$$

where $VO_2(t)$ is the VO_2 at time t; $A0$ is the VO_2 value at rest; and $A1$ and $A2$, TD_1 and TD_2 and τ_1 and τ_2 are the asymptotic amplitudes, time delays and time constants of the fast and slow VO_2 components, respectively.

As the warm-up protocol was present 10 min before the start of both tests, we could not measure pure resting VO_2. Therefore, A_0 as the VO_2 value at the beginning of the fast phase was used. In the parameter searching process, the data before the beginning of the fast component were ignored; therefore, our analysis excluded the cardio-dynamic phase similarly to other studies (Jones and Burnley, 2009; Roberts et al., 2005; Sousa et al., 2014; Sousa et al., 2015; Volianitis et al., 1999).

Identification of the endpoint of the fast phase and determining the characteristics of the VO_2 slow component was made by consideration of a following collection of constraints:

(1) Parameters $A1$, $A2$, $TD1$, $TD2$, τ_1 and τ_2 could not be negative

(2) $\tau_1 \geq 10$ s

(3) $\tau_2 \leq 300$ s

(4) $\tau_2 \geq 3 \cdot \tau_1$

(5) $70 \leq TD_2 \leq 180$

Using the equation from Byrne et al. (2005) we further calculated the value for the resting oxygen consumption (A_0') for every subject. The value of A_0' was subtracted from the value of oxygen uptake at the end of the fast component to determine the physiologically relevant amplitude of the fast component (A_1') (Figure 2). Likewise, the amplitude of the slow component (A_2') was calculated as a difference between value at t=400 s and value at the beginning of the slow component. A_1' and A_2' were presented in preference to the extrapolated asymptotic values.

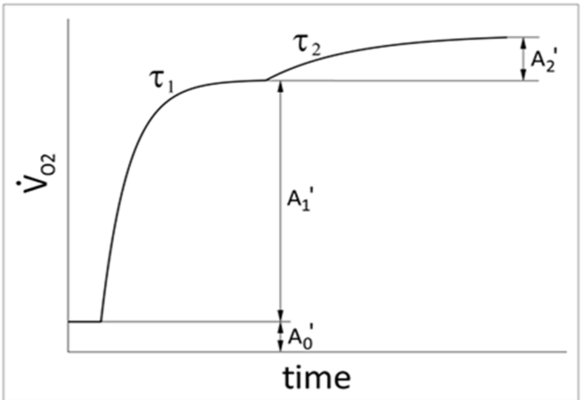

Figure 2. Fast and slow **c**omponents of VO_2 kinetics. A_0' is a calculated value for the resting oxygen consumption, A_1' and A_2' are calculated amplitudes for fast and slow phase, respectively; τ_1 and τ_2 are time constants for the same phases (i.e., the time required to achieve 63% of the amplitude).

4.7 Statistical analysis

The data were analyzed using SPSS for Windows (SPSS, Inc, Chicago, IL, USA). All results were expressed as mean ±SD. The data were checked for normality and the Wilcoxon signed-rank test was used to calculate performance changes in parameters over time if data were nonparametric (Paper I and II). If data were normally distributed a paired samples t-test was used for analysis (Paper III). The relationships between VO_2 kinetics parameters and VO_2 were examined using Spearman's correlation coefficient.

Effect sizes were calculated as Cohen's d. Interpretation of the strength of the effect size coefficients is based on guidelines provided by Hopkins (2009): 0–0.09, trivial; 0.10–0.29, small; 0.30–0.49, moderate; 0.50–0.69, large; 0.70–0.89, very large; 0.90–0.99, nearly perfect; and 1.00, perfect.

Statistical significance was set at $p<0.05$ for all the tests.

5. RESULTS

5.1 Preliminary study (unpublished data)

During maximal all-out rowing ergometer tests time, lactate concentration and rated perceived exertion (RPE) values are presented in Table 2. Maximal inspiratory pressure (MIP), measurements before, immediately after and 30min following 1000m and 2000m all-out rowing tests are also shown in Table 2. Both, MIP values immediately post-test (1 min) and 30 min post-test were significantly ($p<0.05$) lower than baseline MIP values in 1000m and 2000m rowing ergometer tests.

Table 2. Average (±SD) results of 1000m and 2000m all-out rowing test and maximal inspiratory pressure (MIP) values pre- and post-test in 12 national level male rowers (Preliminary study, unpublished data).

	1000m	2000m
Time (s)	189.67±7.05	391.73±16.56
La 3min (mmol/L)	16.01±2.70	15.88±3.51
La 5min (mmol/L)	15.29±3.07	14.81±2.47
RPE (20-pt scale)	17.17±1.11	18.25±1.48
MIP baseline value (cmH_20)	146.75±26.03	153.75±24.55
MIP 1min post-test (cmH_20)	111.33±28.68*	122.50±29.28*
MIP % change 1min post-test (%)	23.50±15.39*	19.84±15.79*
MIP 30min post-test (cmH_20)	131.17±24.66*	138.41±25.93*
MIP % change 30min post- test (%)	9.75±12.31*	9.54±11.81*

La – lactate concentration; RPE – rating of perceived exertion; MIP – maximal inspiratory pressure.
*– significantly different from baseline MIP value ($p<0.05$)

5.2 The effect of inspiratory muscle warm-up on submaximal rowing performance (Paper I)

The spirometry and MIP values of the subjects were compared to the reference values (Evans and Whitelaw, 2009; Kuster et al., 2008) of the healthy population (Table 3).

Tabel 3. Spirometry and maximal inspiratory pressure values of the subjects (mean±SD).

	Subjects (n=10)	
	Actual value	**% predicted**
FVC (l)	6.61±0.43	112.7±9.5
FEV_1 (l)	5.64±0.52	113.8±6.4
PEF (l/s)	11.70±1.28	99.0±11.0
PIF (l/s)	10.98±1.56	110.5±17.0
MIP (cm H_2O)	140.7±46.6	127.4±42.2

FVC – forced vital capacity; FEV_1 – forced expiratory volume in 1 second; PEF – peak expiratory flow; PIF – peak inspiratory flow; MIP – maximal inspiratory pressure.

Table 4 presents the results of the incremental rowing ergometer test where the maximal oxygen consumption was measured and the corresponding Pa_{max} was calculated for the reference to perform the two following experimental rowing tests at the intensity of 90% of Pa_{max}.

Table 4. The mean results of the incremental rowing test.

	Subjects (n=10)		
	Mean ± SD	**Min**	**Max**
Rowing experience (y)	8.5±3.2	4.5	12.0
Pa_{max} (W)	328.7±40.0	275.0	383.0
P_{max} (W)	357.2±33.8	300.8	400.0
VO_{2max} (l/min)	5.0±0.4	4.3	5.7
$VO_{2/kg}$ (ml/min/kg)	58.9±4.8	49.0	65.0

Pa_{max} – maximal aerobic power; P_{max} – maximal power; VO_{2max} –maximal oxygen consumption; $VO_{2/kg}$ – maximal oxygen consumption per kg of body mass.

Table 5 presents the results of the two continuous intensity rowing tests: Test 1 and Test 2, where the subjects had to perform at 90% Pa_{max} after the standard rowing warm-up and the standard warm-up with the additional inspiratory muscle warm-up, respectively. The only measured parameter that reached statistical significance was breathing frequency ($p=0.039$) with no further significant differences between the parameters of the two tests. However, there were tendencies ($p\leq0.1$) towards higher ventilation, lower heart rate and higher RER during Test 2 when we used inspiratory muscle warm-up prior to the test.

Table 5. The results of the two 90% Pa_{max} intensity tests using only traditional rowing warm-up (Test 1) or using traditional warm-up with the additional inspiratory muscle warm-up (Test 2).

	Test 1	Test 2	*p*	% change
Time (min)	13.8±3.0	14.0±2.7	0.575	1.4%
Distance (m)	3991.4±808.8	4044.6±244.1	0.453	1.3%
La pre (mmol/l)	1.63±0.5	1.34±0.7	0.258	–17.8%
La post 3 (mmol/l)	11.8±3.2	12.4±3.1	0.441	5.1%
La post 5 (mmol/l)	10.9±2.7	11.6±3.2	0.395	6.4%
VO_2 (l/min)	4.8±0.4	4.73±0.4	0.543	–1.5%
$VO_{2/kg}$ (ml/min/kg)	56.3±4.6	55.9±6.0	0.526	–0.7%
V_E (l/min)	155.9±20.0	159.4±20.4	0.100	2.2%
HR (min^{-1})	177.2±7.5	174.1±8.0	0.067	–1.7%
RER	1.11±0.7	1.14±0.7	0.097	2.7%
BF (min^{-1})	52.2±6.8	53.1±6.8*	0.039	1.7%

La pre – lactate concentration before submaximal performance; La post – lactate concentration after submaximal performance; VO_2 – peak oxygen consumption; VO_2/kg – oxygen consumption per kg bodyweight; V_E – minute ventilation; HR – heart rate; BF – breathing frequency; RER – respiratory exchange ratio. *– significantly different from Test 1 value, p<0.05.

5.3 Maximal inspiratory pressure is influenced by intensity of the warm-up protocol (Paper II)

Table 6 presents the mean MIP values before and after different intensity IM warm-up protocols. The recorded MIP was significantly higher after acute IM warm-up using 40% of MIP (p=0.047) and 60% of MIP intensity (p=0.027). Individual differences in MIP values can be seen in Figure 5.

Table 6. The mean values (±SD) of MIP before and after different inspiratory muscle warm-up protocols.

	n	Baseline (cmH_2O)	Post-IM warm-up (cmH_2O)	*p*-value	Warm-up load
15% MIP 2×30 inspirations	10	129.0±38.5	135.2±38.3	0.089	1157.4±328.3
40% MIP 2×30 inspirations	9	135.7±42.9	142.7±42.7*	0.047	3168.0±958.3[1]
60% MIP 2×12 inspirations	10	134.0±38.7	140.4±38.4*	0.027	1955.4±528.3[1,2]
80% MIP 2×6 inspirations	10	137.0±46.0	145.9±38.9	0.108	1315.2±418.9[2,3]

*Significantly different from baseline value; [1]Significantly different from 15% MIP load; [2]significantly different from 40% MIP load; [3]significantly different from 60% MIP load; for all comparisons p<0.05; IM-inspiratory muscle; MIP-maximal inspiratory pressure.

The performed load during warm-up sessions was significantly higher for the 40% and 60% MIP test compared to the 15% and 80% MIP test ($p<0.05$). Performed load was also higher for the 40% MIP compared to the 60% MIP test ($p=0.003$) while no differences were seen in the 15% MIP test compared to the 80% MIP test ($p=0.39$).

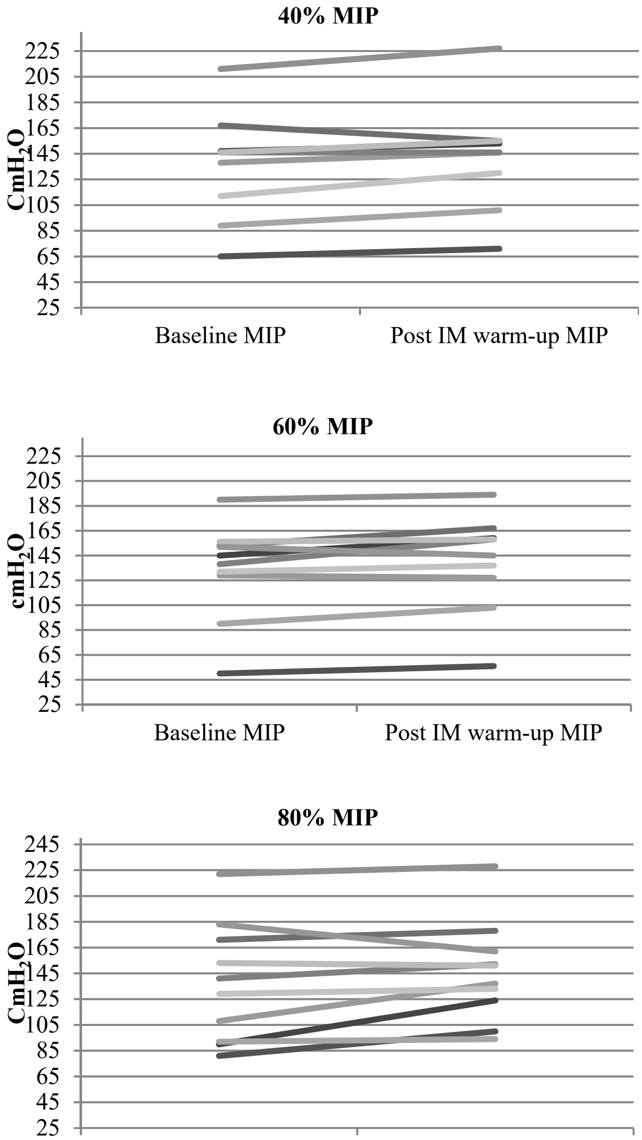

Figure 5. Differences in individual MIP values from baseline after 40%, 60% and 80% of MIP intensity inspiratory muscle (IM) warm-up. Statistically significant differences were seen in 40% and 60% of MIP intensity warm-up ($p=0.047$ and $p=0.027$, respectively).

5.4 The Effect of Inspiratory Muscle Warm-Up on VO_2 Kinetics during Submaximal Rowing (Paper III)

The parameters of the VO_2 response from the submaximal intensity rowing tests with two different warm-up protocols are reported in Table 7. The VO_2 data from one subject did not fit to the exponential curve for the slow component; therefore, we excluded his data from VO_2 slow component. No significant differences in any VO_2 kinetics parameters were found between the two test protocols.

Table 7. Parameters of the VO_2 kinetics during two rowing tests at 90% VO_{2max} with traditional rowing warm-up (Test 1) and with traditional rowing warm-up with specific inspiratory muscle warm-up (Test 2)

	N	Test 1	Test 2	% change	*p*	*Effect size (Cohen´s d)*
A_0' (l/min)	10	0.26±0.02	0.26±0.02	0	–	–
τ_1 (s)	10	19.50±5.80	19.26±5.20	–1.6%	0.69	0.04
A_1' (l/min)	10	4.30±0.35	4.28±0.42	–0.5%	0.75	0.05
TD_2 (s)	9	128.32±35.16	125.52±33.18	–2.2%	0.88	0.08
τ_2 (s)	9	105.56±64.00	101.17±61.51	–4.2%	0.83	0.07
A_2' (l/min)	9	0.26±0.16	0.28±0.17	7.7%	0.83	0.12
VO_2 **at 400 s (l/min)**	9	4.86±0.13	4.84±0.14	–0.4%	0.76	0.15

Values are mean ± SD; A_0' – baseline oxygen consumption; τ_1 – time constant of the fast component; A_1' – amplitude of the fast component; TD_2 – time delay of the slow component; τ_2 – time constant of the slow component; A_2' – amplitude of the slow component

Table 8 presents the correlations between different parameters describing the VO_2 kinetics during the two submaximal rowing performance tests. There was a significant positive correlation between τ_1 and A_1' (r=0.85), and between τ_1 and VO_2 value at 400 sec (r=0.78) in Test1, but both of those correlations disappeared in Test2. In both tests A_1' was strongly correlated with the VO_2 value at 400 sec (r=0.91 and r=0.92, respectively).

Table 8. Correlation coefficients between VO_2 kinetics parameters.

	Test 1				**Test 2**			
	τ_1 (s)	**τ_2 (s)**	**VO_2 at 400 s**	**A_1' (ml/min)**	**τ_1 (s)**	**τ_2 (s)**	**VO_2 at 400 s**	**A_1' (ml/min)**
τ_2 (s)	.49				.50			
VO_2 at 400s	.78*	.50			.21	.04		
A_1'(ml/min)	.85*	.34	.91*		.33	–.08	.92*	
A_2'(ml/min)	–.09	.40	.28	–.14	–.53	.29	.15	–.26

τ_1 – time constant of the fast component; A_1' – amplitude of the fast component; TD_2 – time delay of the slow component; τ_2 – time constant of the slow component; A_2' – amplitude of the slow component. * – Correlation is significant at the 0.05 level (2-tailed).

We found also a significant correlation between VO_{2max} measured during the incremental rowing test and τ_1 from Test1 ($r=0.71$; $p<0.05$), whereas VO_{2max} did not correlate with τ_1 from Test 2 (Figure 6).

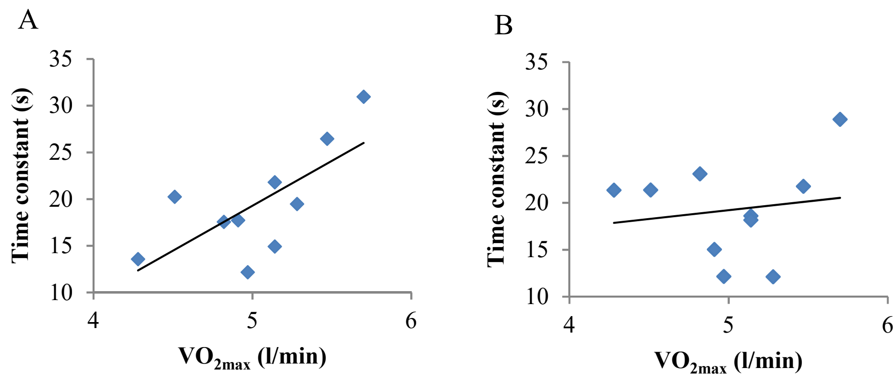

Figure 6. Relationship between maximal oxygen consumption (VO_{2max}) and time constant of the fast component (τ_1) during Test 1 (A) ($p<0.05$) and Test 2 (B) ($p\geq0.05$).

6. DISCUSSION

The purpose of the current thesis was to investigate possible effects of an acute bout of specific inspiratory muscle warm up on different physiological and performance related parameters of rowing ergometer performance. Therefore, we aim to expand our understanding about the fatigue of the respiratory muscles during rowing, IM warm-up in general and what could be the role of inspiratory muscle warm-up´s inclusion to different parameters of the respiratory system, rowing performance and VO_2 kinetics.

6.1 Inspiratory muscle fatigue following 1000m and 2000m rowing test (Unpublished data)

Previously it was thought that the respiratory system is not a limiting factor of athletic performance. However, it has been shown that the fatigue of the respiratory muscles may play a role in the decrease of athletic performance. It is less known how the inspiratory muscle function can be improved by adding the specific inspiratory muscle warm-up to traditional warm-up. Studies have indicated that the fatigue of the IM and metabolite accumulation in respiratory muscles during intense exercise might cause a „steal phenomenon "– to preserve the respiratory muscle perfusion the blood flow to the exercising limb muscles is reduced by means of reflex vasoconstriction, thereby constraining oxygen uptake and limiting exercise tolerance (Dempsey et al., 2006; Kolkhorst et al., 2004). By increasing the proportion of type I fibers in respiratory muscles may enhance their economy and may help to delay the respiratory muscle metaboreflex. The mechanisms, and how IM training and warm-up may influence these factors and how they affect exercise performance is not well researched (Shei, 2018).

Inspiratory muscle fatigue can change performance already in 100m swimmers as shown by Muranaka et al. (2021). Seven swimmers had to swim all-out 100m in two conditions – with or without IM fatigue. In test that followed IMF, swimming time was significantly longer compared with that in control swimming without IMF (55.94±1.15 s vs 54.09±0.91 s) ($p<0.05$). When swimming tests were carried out after IMF the sense of dyspnea was significantly higher compared to the control condition. Similarly, Lomax and Castle (2011) found that when a 17% decrease in MIP was induced (IMF), it caused an increase in total breaths taken and breaths per minute during 200m swimming test compared to control test. In rowers, Volianitis et al. (1999) showed that following the incremental rowing test to exhaustion, MIP decreased by 7.0 ± 2.0 %, which is considered respiratory muscle fatigue.

In our preliminary study (unpublished data) we measured MIP after 1000 m and 2000 m all-out rowing tests and registered the average percentage decrease by 23.5±15.4% and 19.8±15.8%, respectively. Similarly, we measured MIP 30 min after the 1000 m and 2000 m all-out rowing, and found the average decrease to be 9.8±12.3% and 9.5±11.8%, respectively. This shows that after the regular rowing race distances the inspiratory muscles can fatigue and it may also indicate that it takes longer time to recover than 30 min. In rowing regattas, it might be necessary to compete twice per day and in the second race the IM fatigue may play an important role of the possible performance decrease. Therefore, the IM warm-up could be an important addition before races to better prepare the respiratory system.

6.2 The effect of inspiratory muscle warm-up on submaximal rowing performance (Paper I)

The purpose of the paper was to investigate the effect of acute inspiratory muscle warm-up on submaximal rowing performance, post-exercise lactate concentration and breathing values. The main finding of the study was that the inspiratory muscle warm-up at 40% of MIP before submaximal rowing exercise does not enhance performance significantly in well trained male rowers. However, it might have some effect on physiological parameters, as inspiratory muscle warm-up caused statistically higher breathing frequency.

In this study, we measured the difference between two submaximal rowing performance tests (with, or without additional inspiratory muscle warm-up) and did not find any significant difference in time or distance covered during the sub-maximal rowing ergometer test, performed at the intensity of 90% Pa_{max}. Some authors have found that inspiratory muscle fatigue causes sympathetic blood flow restriction in limb muscles to ensure the work of the respiratory muscles (Sheel et al., 2001; St Croix et al., 2000). Therefore, one of our hypotheses was that by adding inspiratory muscle warm-up to the standard rowing warm-up there would be a positive influence on rowing performance due to delaying inspiratory muscle fatigue and consequently, the blood flow to the limbs would not be affected in the later stage exercise (Burnley et al., 2003; Harms et al., 2000). Furthermore, the slumped position and stroke frequency dependent breathing rhythm in rowing might inhibit the ability of the diaphragm to work and might lead to earlier fatigue of the inspiratory muscles. Therefore, a stronger and more efficient respiratory system might help to maintain the limb blood flow for longer period and enhance the performance of the athlete (Witt et al., 2007).

In their study, Holm et al. (2004) showed that all subjects who had higher ventilation after inspiratory muscle training performed better due to the finding that their breathing frequency was higher. They were also able to tolerate increa-sed ventilatory loads without an increase in dyspnoeic sensation. In the current study we also found that breathing frequency was significantly higher ($p<0.05$) during Test 2. In addition, ventilation indicated a tendency to be higher ($p=0.1$) and heart rate to be lower ($p=0.067$). Therefore, despite unaltered performance, it seems that an acute bout of inspiratory muscle warm-up might cause some changes in the ventilatory system by altering breathing frequency and might also lower heart rate. If compared to other studies, none of our subjects had a high enough breathing frequency to constitute hyperventilation, which has considered as a sign of respiratory muscle fatigue (Bateman et al., 2006). Therefore, the increase in breathing frequency in our study should not be considered as a negative sign, but more as a possibility to increase ventilation without becoming dyspnoeic.

The main difference in our study compared to the previously conducted studies is the control of the exercise intensity used during both tests. While Volianitis et al. (2001B) used a maximal intensity test, we used the intensity of 90% Pa_{max}. However, we set the time of the tests limited to maximal 20 min because changes in the respiratory system should have occurred already by that time. The submaximal intensity was used because the all-out or maximal tests are highly dependent on the subjects' motivation and willingness to perform maximally, which could significantly affect the results. Fixed intensity test gives an opportunity to measure the physiological response in constant terms. However, the negative aspect would be that it does not reflect the actual rowing performance that can predict the success during the competitions, and we can't say whether the inspiratory muscle warm-up has any effect on all-out rowing performance (McConnell and Romer, 2004). Previous studies have indicated that the 2000m rowing race corresponds approximately to the 95% of VO_{2max} (Cosgrave et al., 1999). If comparing VO_2 during the submaximal tests (56.3±4.46 and 55.9±6.0 for Test1 and Test 2, respectively), we can see that it corresponds to about 94–95% of the VO_{2max} of the subjects (58.9±4.9). Therefore, we can argue that the intensity used in the test was in a range where we could simulate the stress a traditional rowing race has on the respiratory system. Although not statistically significant, the participants in our study were able to row for a longer period (1.45%) and covered slightly longer distances (1.33%) when inspiratory muscle warm-up was added to the traditional rowing warm-up. However, the mean change of the performance was comparable to other studies (Volianitis et al., 2001A; Volianitis et al., 2001B; Wilson et al., 2013).

There are very few studies that have measured the effect of inspiratory muscle warm-up on blood lactate concentration (Lin et al., 2007). We hypothesized that inspiratory muscle warm-up might decrease blood lactate concentration after Test 2 due to the increased economy of the inspiratory muscles. Previous studies have shown a decrease in blood lactate after inspiratory muscle training and the reason might be the result of a better reusage of lactate by increasing blood flow to the diaphragm and other respiratory muscles (Romer et al., 2002; Spengler et al., 1999). Another reason for the reduction might be due to the lower lactate production of the respiratory muscles while performing at the same intensity (Brown et al., 2010) and due to faster warming-up of the respiratory system at the beginning of the test. In our study we did not see any changes in lactate concentration between the two tests, which could suggest that there is no effect of inspiratory muscle warm-up on submaximal blood lactate concentration during 10-to-15-minute exercise at the intensity of 90% Pa_{max}. It must be also taken into consideration that the used 90% Pa_{max} intensity might serve as warm-up itself for inspiratory muscles, as the subjects do not start the tests at their maximum effort.

This in fact might stress inspiratory muscles at slightly lower individual level and could result in higher inter-individual response depending on the capacity of the respiratory system. Further research is needed to conclude its influence on the results of the current investigation. Nevertheless, the current inspiratory muscle warm-up protocol was not found to have an influence on submaximal rowing ergometer performance.

Previous studies have found that inspiratory muscle warm-up with 40% MIP positively affects the performance of rowers during a 6-min "all-out" test, badminton players and runners performing the Yo-Yo test (Lin et al., 2007; Tong and Fu, 2006; McConnell et al., 2004; Volianitis et al., 2001). Similarly, Wilson et al. (2013) recently showed a positive effect on 100-meter swimming performance using a 40% MIP warm-up. All these performances related to high intensity performance (approximately 100% VO_{2max}). However, Leicht et al. (2010) demonstrated that using inspiratory muscle warm-up on active paraplegic individuals did not benefit from the commonly used intensity of 40% MIP. As we also did not see any performance change after inspiratory muscle warm-up during submaximal intensity, the use of different intensities of inspiratory muscle warm-up could be the aim of future studies, for example to be able to achieve a "faster start" during performances longer than 8–10 minutes.

In summary, we conclude that an acute bout of inspiratory muscle warm-up at 40% MIP prior to submaximal rowing has no significant influence on respiratory parameters to improve rowing performance despite significantly increased breathing frequency. Further research is needed to better understand the effect of an acute session of inspiratory muscle warm-up and its implications on athletes prior to competition at different intensities. The possible reasons why we did not see any significant difference in test duration nor distance covered, might be the inspiratory muscle load used during the warm-up (40% MIP) and the choice of submaximal performance intensity on a rowing ergometer (90% Pa_{max}).

6.3 Maximal Inspiratory Pressure is influenced by intensity of the warm-up protocol (Paper II)

Based on the previous studies and by the progressive model of traditional strength training we hypothesized that IM would react to stimuli the same way as other skeletal muscles (Kraemer et al., 2002) and a higher intensity of IM warm-up would better prepare the respiratory system compared to the commonly used two sets of 30 repetitions at 40% MIP. This has not been done previously on IM muscle training or warm-up studies. A higher intensity and smaller number of inspirations during IM warm-up would mimic the higher respiratory loads that occur during sporting activities (Rehdes-Santos et al., 2021). The aim of the paper was to assess the acute effect of different IM warm-up intensities on MIP. The main result was that the 40% and 60% MIP warm-up protocols resulted in significant increases in MIP values. Other intensities (15% and 80% of MIP) did not have any statistically significant effect on MIP.

Previous research on whole body warm-up exercises has shown that warm-up protocols with higher intensities better prepare the athlete to compete in intermittent intensity sports activities (Saez Saez de Villarreal et al., 2007; Zois et al., 2013 and Zois et al., 2015). According to our results similar phenomena might apply for inspiratory muscles. If athletes use higher intensity (60% of MIP) inspiratory muscle warm-ups with two sets of 12 inspirations, they could shorten the duration of the warm-up as compared to previously used beneficial IM warm-ups utilizing two sets of 30 inspirations at a lower intensity. This might become a useful factor when practicing or competing in hot environments where longer duration warm-up may negatively affect athletic performance (Wüthrich et al., 2015).

In previous research the commonly used intensity of IM warm-up has been 40% of MIP with two sets of 30 inspirations. This level of intensity was hypothesized to approximate the upper loading limit before fatigue of the diaphragm occurs (Volianitis et al., 2001a). However, the results from Sheel et al. (2001) indicated no evidence of IM fatigue after three minutes of inspiratory resistive loading (IRL) against 80% or 95% of MIP. These results seem to advocate for the use of intensities higher than 40% MIP for IM warm-up, thus achieving shorter warm-up duration (<3 min) without causing IM fatigue. Also, McConnell and Griffiths (2010) have recently shown that acute IRL at 60% of MIP elicited a sustained rise in systolic blood pressure and mean arterial blood pressure after 60 seconds, providing evidence for a metaboreflex response at this load, while lower and higher intensities did not have similar effect. Interestingly, Klusiewicz et al. (2008) investigated the effect of six weeks of IM training in elite rowers using a load of 50% of MIP and found no change in MIP. Although in this case it was not a warm-up but 6-weeks of IM training, a significant increase in IM training was found when using a load of ~62% of MIP. These findings may also indicate the benefit for a higher intensity IM training than previously used 50% of MIP load.

Previous research that has focused on IM warm-up at 40% MIP with 2×30 inspirations have shown an increase in MIP after IM warm-up with the range of increase from 6.9% to 9.1% (Johnson et al., 2014; Lin et al., 2007; Tong and Fu, 2006; Ohya et al., 2015; Volianitis et al., 1999; Volianitis et al., 2001A and Volianitis et al. 2001B; Özdal, 2016;). In our study we found a statistically significant ($p<0.05$) increase in MIP from baseline after IM warm-up with 40% of MIP and with 60% of MIP with the mean increase in MIP being 4.8% (135.7 ± 42.9 to 142.7 ± 42.7 cm H_2O) and 5.1% (134 ± 38.7 to 140.4 ± 38.4), respectively. One possible explanation for a smaller change in MIP compared to other studies could be the relationship between the baseline MIP value and IM warm-up induced increase in MIP. Brown et al. (2014) showed that baseline MIP explained 23% of the variance in change of the MIP values after IM training, with this change being larger in those with a lower baseline MIP. Similarly, with non-respiratory skeletal muscles, the closer the muscles are to their physiological limits, the smaller is the potential for reaching that limit. Our subjects were healthy active men whose MIP values were similar with other studies; therefore, the baseline MIP value is probably not the main reason for a smaller increase in MIP after the IM warm-up. Volianitis et al. (2001B) suggested that the effect of IM warm-up can be more visible in subjects well acquainted with the Mueller maneuver and since our subjects had not used this maneuver before, this could provide one explanation for the smaller change in MIP.

The exact basis for the increase in MIP observed after IM warm-up is yet to be resolved. In contrast with structural adaptations occurring after several sessions of IM training (McConnell and Romer, 2004), improved motor unit recruitment and increased synergy between active inspiratory muscles could be predominant mechanisms responsible for increase in IM strength after IM warm-up (Lomax and McConnel, 2009; Lomax et al., 2011). Butler et al. (1995) suggested that the sudden loading of the IM may produce a reflex inhibition of motor neurons. IM warm-up may improve intramuscular coordination and remove some of this reflex inhibition, resulting in greater force generation (Volianitis et al. 2001B). In addition, prior exercise can help muscles to achieve their optimum reactive O_2 species (Reid, 2001) and improve the conditions for O_2 delivery (Behnke, 2002; Poole and Jones, 2012), which both can increases contractile performance of IM.

The advantages of the MIP test are that it is non-invasive and simple to perform, there are hand-held devices available, and the measurement is well standardized (ATS/ERS, 2002). For our MIP results we chose to use the highest value out of three attempts which were found as maximal pressure sustained for 1 second as suggested in the standards as this should give more reproducible results than using the peak pressure (ATS/ERS, 2002). Dimitriadis et al. (2011) assessed the reliability of MIP measurement with MicroRPM and reported the intraclass correlation coefficient to be higher than 0.9. However, it should be taken into consideration that the MIP test is dependent on voluntary effort of the subject and therefore, it requires full understanding of the task to be performed with maximal participant effort and verbal encouragement from the tester (Sclauser Pessoa et al., 2014). Studies have shown that the learning effect is the main reason for the large inter-study variations in the MIP values (Lomax and McConnell, 2009; Terzi et al., 2009). To minimize the learning effect, we used five to seven MIP tests for familiarization prior to starting the study as recommended by Dimitriadis et al. (2011). We had to exclude data for one warm-up protocol as the baseline MIP value in one subject was significantly lower than his other baseline (and post IM warm-up) values and since the warm-up intensity was calculated from the baseline MIP, using this outlying MIP value could have influenced the whole protocol.

6.4 The Effect of Inspiratory Muscle Warm-Up on VO_2 Kinetics during Submaximal Rowing (Paper III)

To best of our knowledge, this was the first study to compare the oxygen consumption kinetics during high intensity rowing with different warm-up protocols – one with the regular rowing warm-up and the other with the regular rowing warm-up with the added inspiratory muscle warm-up (IM-WU). The hypothesis of the current study was not supported, as we did not find any significant differences in the fast and slow component of VO_2 kinetics between the two warm-up protocols.

As we have previously mentioned, performing warm-up before exercise is common in different sports and used regularly in order to influence the physiological response to subsequent exercise. Several studies have shown that specific inspiratory muscle training or warm-up can increase the strength of the inspiratory muscles and therefore, also delay IM fatigue and may have positive effects on sport performance (Illi et al., 2012; Roberts et al., 2005; Volianitis et al., 1999).

Previous studies have reported time constants for the fast phase of oxygen kinetics (τ_1) ranging from 35 to 50 seconds in normal subjects, approximately 15–30 seconds in highly trained athletes and 63–75 seconds in patients with cardiopulmonary disease (Bailey et al., 2012; Byrne et al., 2005; Hopkins et al., 2009; Sousa et al., 2015; Whipp, 1994; Whipp et al, 2002). In our study the mean values for τ_1 (19.50 and 19.26 seconds for Test1 and Test2, respectively) were similar to those reported previously by Ingham (2007). The elite rowers in their study had faster τ_1 than club level rowers for high-intensity exercise (18.7±2.1 and 22.4±3.7 sec, respectively). Mean τ_1 values from other studies in rowers have been 26.5 sec (Roberts et al., 2005), 23 sec (Demarie et al., 2008), 16 sec (Sousa et al., 2014) and 13.6 sec (Sousa et al., 2015). Therefore, it can be suggested that shorter τ_1 would characterize rowers with higher performance potential.

The recruitment of a greater muscle mass could potentially compromise muscle perfusion, particularly during heavy exercise where a larger fraction of the maximal cardiac output is used by active muscles. If muscle perfusion would be a limiting factor for VO_2 kinetics, this would result in longer τ_1 when a greater muscle mass is recruited (e.g., in rowing). Yet, Roberts et al. (2005) showed that pulmonary VO_2 kinetic responses in physically active men in moderate and heavy intensity exercises during upright cycle and rowing ergometer exercises were similar. Koga et al. (2001) also reported that there were no significant differences in τ_1 between one-legged and two-legged cycle ergometry for either moderate or heavy exercise. If τ_1 is not significantly altered by the recruitment of a greater muscle mass, this could suggest that O_2 availability does not limit VO_2 kinetics even during heavy exercise involving a large muscle mass (Roberts et al., 2005). In case the work rates were sub-maximal, like in our tests, cardiac output could be increased during rowing exercise to ensure that muscle perfusion in all areas (i.e., legs, arms and also respiratory muscles) was adequate. This could be the reason why adding the IM-WU could not improve the perfusion of exercising muscles and did not change the fast component of the VO_2 kinetics in our study (both τ_1 and A_1' were similar in two tests, Table 7).

It has been suggested that the VO_2 slow component (τ_2) is primarily linked to the progressive recruitment of motor units with higher order (type II or fast twitch) fibers in the exercising muscle during prolonged submaximal exercise (Barstow et al., 1996; Poole et al., 1991, 2008; Vanhatalo et al., 2011). High-performing rowers should show higher proportion of type I fibers and therefore, smaller VO_2 slow component might be expected. However, slow component in elite rowers has been reported higher because of the greater power outputs performed (Ingham et al., 2007). Training or warm-up could enhance the recruitment of type I fibers and, therefore, would diminish the VO_2 slow component and would indicate an improved exercise economy/efficiency (Carter, 2000; Ingham, 2007; Reis et al., 2012). We could not find significant differences in parameters related the VO_2 slow component between two tests in our study. The mean values for τ_2 (105.56 and 101.17 seconds for Test 1 and Test 2, respectively) were close to those reported previously in rowers (109.6 sec) in a study by Demarie et al. (2008). However, there have been indications for quite different τ_2 values in the literature. For example, in one study the mean values for τ_2 during high-intensity exercise were 207 sec in club level and 242 sec in elite rowers (Ingham et al., 2007), whereas in another study the mean value for τ_2 was only 48.4 sec (Sousa et al., 2015). However, the main reason for those high discrepancies is probably due to differences in used intensities during the measured tests.

Similarly, there are quite different results for the amplitude of the slow component (A_2) in studies of VO_2 kinetics in rowers (Ingham et al., 2007; Markovitz et al., 2004; Roberts et al., 2005; Sousa et al., 2014;). This can mostly be explained by differences in the training status/history, power outputs performed by groups of subjects and therefore differences in the maximal VO_2 achieved during the test. The mean values for A_2 and VO_{2max} (at 400 sec) did not change after adding inspiratory muscle warm-up (from 0.26 to 0.28 l/min and 4.86 and 4.84 l/min, respectively). In relative terms, the amplitude of the slow phase in current study was quite low: 5.4% of the maximal VO_2 in Test1, and 5.8% in Test 2. Other studies with rowers have shown very different maximal VO_2 values (in a range 3.15–5.09 l/min) and corresponding A_2 values ranging from 6.7–10.7% (Ingham et al., 2007; Roberts et a., 2005; Demarie et al., 2008). As A_2 amplitude is affected by the used intensity during the exercise, the future studies should rather focus on constant, but relatively high submaximal intensities to investigate potential effect of IM-WU. The use of maximal intensity test to study the effect of the IM warm-up might be complicated due to potentially different pacing strategies between the subjects, where some tend to start at higher pace compared to others, or the motivation for producing maximal effort might be different between the tests.

Previous studies have found conflicting results regarding the relationship between τ_1 and VO_{2max}. Some authors have shown shorter time constant in athletes with higher VO_{2max} (Ingham et al., 2007; Markowitz et al., 2004), whilst others have found no correlation between τ_1 and VO_{2max} (Barstow et al. 2000; Pringle et al. 2003, Reis et al. 2012). Interestingly, we observed a significant positive correlation between τ_1 and VO_{2max} from the incremental rowing test and VO_2 value at 400 sec in Test 1, but not in Test 2. Poole and Jones (2008) have suggested a model with two zones demonstrating the effects of altering muscle O_2 delivery on VO_2 kinetics: O_2 delivery independent zone where decrease in O_2 delivery does not change the time constant, and O_2 delivery dependent zone where VO_2 kinetics become slower (i.e., τ_1 becomes larger) with further reduction in O_2 delivery. There is an on-going discussion about whether we can position healthy individuals in a specific place in that model, on either side of the "tipping point" between the two zones, or we have to believe that in a specific exercising subject there may be populations of muscle fibers operating on the right (slow-twitch, non-O_2-delivery limited fibers) and some other fibers – on the left (fast-twitch, O_2-delivery limited fibers) of the tipping point (Jones et al., 2008; Poole et al., 2008). The results of study show that this group of rowers exercised mostly in the O_2 delivery independent zone and therefore, IM warm-up did not change τ_1, and this also caused relatively low slow phase in the group.

7. CONCLUSIONS

Based on the results of the studies, the following conclusions were made:

1. The inspiratory muscle warm-up at 40% of maximal inspiratory pressure (MIP) before submaximal rowing does not significantly enhance rowing performance in well trained male rowers.
2. Inspiratory muscle warm-up at 40% of MIP has a little effect on physiological parameters. An acute bout of inspiratory muscle warm-up caused statistically significant changes in the ventilatory system by altering breathing frequency and might also lower the heart rate frequency in well trained male rowers.
3. Inspiratory muscle warm-up at intensities of 40% and 60% MIP resulted in significant increases in MIP values. Other intensities (15% and 80% of MIP) did not have any statistically significant effect on MIP.
4. Adding inspiratory muscle warm-up of 40% maximal inspiratory pressure (MIP) to regular rowing warm-up had no significant effect on oxygen consumption kinetics during submaximal rowing tests.

8. PRACTICAL APPLICATIONS

In previous research, inspiratory muscle (IM) training has proven a useful method to help perform better in short- and long-term endurance events, but inspiratory muscle warm-up has a less clear effect. Our studies showed that the inspiratory muscles can fatigue already after 1000m rowing test and specific IM warm-up with 40% MIP caused an increase in breathing frequency and a tendency for higher ventilation, RER, and lower heart rate, but did not increase submaximal performance. Also, our studies showed that warm-up protocols with higher intensities of maximal inspiratory pressure increased inspiratory muscle strength, yet it seems to have no effect on VO_2 kinetics. However, the IM warm-up seemed to have no negative effects on performance also. Therefore, coaches and endurance athletes may focus on inspiratory muscle warm-up at 40–60% MIP level to test for individual effects before trainings and competitions to better prepare the respiratory system.

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SUMMARY IN ESTONIAN

Sissehingamislihaste soojenduse mõju sõudjate sooritusvõimele, hapnikutarbimisele ja maksimaalsele suuõõnerõhule sissehingamisel.

Võidu saavutamine tippspordis võib sõltuda mõnest kümnendiksekundist või sentimeetrist – otsustavaks teguriks võib saada treeningu professionaalne planeerimine pisiasjadeni, mis on vastavuses sportlase ja treeneri seatud eesmärkidega. Treenerid ja sportlased on pidevalt otsimas erinevaid võimalusi kehalise töövõime parandamiseks, mis võimaldavad treenida suurema mahu või intensiivsusega. Üheks uuemaks täiendavaks treeningmeetodiks on pakutud ka spetsiifilist sissehingamiselihaste treeningvahendeid. Levinuim treeningvahend selleks on PowerBreathe® (IMT technologies Ltd, Birmingham, UK), mida ka käesolevas töös sõudjatel ja harrastussportlastel kasutati.

Akadeemiline sõudmine oma klassikalise 2000m võistlusdistantsiga on suhteliselt intensiivne spordiala. Sõudmine esitab sportlase skeletilihas- ja kardiorespiratoorsele süsteemile väga kõrged nõudmised – keskmistelt 5–7 minutit kestval sõudmisvõistlustel on olenevalt paadiklassist liigutuste sagedus 33–42 tsüklit minutis. Kopsude minutiventilatsioon võib tõusta kuni 270 liitri minutis, mis võib olla koos küfootilise ja ettekallutatud tõmbe kehaasendiga faktoriteks, miks tekib hingamislihaste väsimus. Ühe tõmbetsükli jooksul tehakse kaks sisse- ja kaks väljahingamist (Mäestu jt, 2005; Volianitis et al., 2020).

Varasemalt arvati, et hingamissüsteem ei ole kõrge intensiivsusega kehalisel tööl limiteerivaks teguriks, kuid üha enam teadusuuringuid tõestavad, et meie keha võime treenida kõrgetel intensiivsustel võib üsna olulisel määral olla limiteeritud hingamissüsteemi võimekusest (Lomax ja McConnell, 2003; Boutellier jt., 1992). Maksimaalse intensiivsuse lähedastel intensiivsustel treenides või võisteldes suureneb sportlaste minutiventilatsioon, mis tähendab, et hingamislihased peavad kontraheeruma suurema jõuga ning kiiremini. Lisaks moodustab maksimaalse intensiivsusega kehalisel tööl hingamistegevuse energiavajadus ligikaudu 15–16% (Harms jt., 2000). Mida tugevamalt hingamislihased töötavad, seda rohkem nad ka energiat vajavad ning seda vähem verd liigub läbi jäsemete. See tähendab, et veri, mis peaks varustama töötavaid lihaseid, kasutatakse järjest enam ära ka hingamislihaste poolt, tagamaks nende tööd (St. Croix jt., 2000; Harms jt., 2000).

Enamikel hästitreenitud inimestel põhjustab kehaline töö füsioloogilist stressi, mis võib pärssida hapniku omastamise võimet (Dempsey ja Wagner, 1999). Kui siia juurde lisada veel, et hingamislihased väsivad sarnaselt meie keha kõikide teiste lihastega, mille peamiseks tunnuseks on hingamismustri muutus, mida iseloomustab hingamismahu ja -sageduse vahekorra muutus viimase kasuks, siis kujuneb kiire ja pindmine hingamine (Sheel jt., 2001). Hingamislihaste väsimust on märgatud juba 200 m maksimumilähedase ujumise testi järgselt, mille tulemusena ei suudetud enam tagada sügavat ja efektiivset hingamist ja tugevnes subjektiivne aisting, et keha ülejäänud lihased peavad rohkem tööd tegema (Lomax ja McConnell, 2003).

Treenerid ja sporditeadlased on regulaarselt kasutanud maksimaalse hapnikutarbimise (VO_{2max}) ja sellega seonduvate parameetrite jälgimist vastupidavusalade sportlaste töövõime ning treeningmeetodite hindamiseks, et aidata energiatootmise protsesse tõhustada. Erinevate treening- ja võistluseelsete soojenduste ning aktivatsiooni-harjutuste eesmärk on tõhustada närvilihasaparaadi ja kardiorespiratoorse süsteemi toimimist. Hapnikutarbimise tõusu jälgimisel kehalise töö alguses eristatakse kiiret ja aeglast komponenti, mis aitab paremini mõista muutusi, mis tagavad töötavate lihaste hapnikuga varustamise (Barker jt., 2010; Sousa jt., 2014).

Konstantse intensiivsuse korral on VO_2 tõus puhkeoleku väärtuselt koormusele vastava väärtusele tervetel noortel sportlastel kiirem kui mittetreenitud isikutel (Jones ja Burnley, 2005; Poole ja Jones, 2012). Seda lühemat ajakonstanti seostatakse paranenud koormustaluvuse ja võimekusega jalgratturitel, jooksjatel ja sõudjatel (Burnley ja Jones 2007; Ingham jt., 2007; Whipp jt., 2002). Samuti on leitud, et suurem hapnikutarbimise kiire komponendi amplituud on otseselt seotud paremate 400 m krooliujumise tulemustega (Fernandes jt., 2009). Koppo jt (2002) näitasid, et koormustõusule vastava VO_2 kiire komponendi ajakonstant oli kätekõverduste puhul pikem kui ajajäsemete harjutuste puhul. Siiski näitas Robertsi jt (2005) uurimus, et mõõdukate ja suurte koormuste korral oli maksimaalse hapnikutarbimise (VO_2) muutuste kiirus (püstise) veloergomeetri ja sõudeergomeetri uuringutes sarnane.

Lisaks on mitmed uurimisrühmad näidanud, et pikemaajalisem sissehingamislihaste treening parandab hästitreenitud sportlastel sissehingamislihaste jõudu ja sooritusvõimet (Lin jt., 2007; Tong ja Fu, 2006; Lomax ja McConnell 2003; Romer jt., 2002; Volianitis jt., 2001A ja B). Vähem on aga uuritud ainult ühekordse sissehingamislihaste soojenduse kasutamist enne koormust ja selle mõju sooritusvõimele (Lin jt., 2007; Tong ja Fu, 2006; Volianitis jt., 2001B).

Töö eesmärk ja ülesanded

Käesoleva doktoritöö eesmärk oli uurida spetsiifilise sissehingamislihaste soojenduse mõju erinevatele füsioloogilistele parameetritele ja sportlikule sooritusvõimele sõudjatel.

Konkreetsemad ülesanded püstitati järgnevalt:

1. Võrrelda submaksimaalsel sõudmisel sõudeergomeetril spetsiifilise sissehingamislihaste soojenduse (intensiivsusel 40% maksimaalsest suuõõnerõhust sissehingamisel, MIP) mõju maksimaalse hapnikutarbimise aeglasele komponendile (I uuring).

2. Võrrelda submaksimaalsel sõudmisel sõudeergomeetril spetsiifilise sissehingamislihaste soojenduse (intensiivsusel 40% maksimaalsest suuõõnerõhust sissehingamisel) ja traditsioonilise sõudjate soojenduse mõju laktaadi kontsentratsioonile, ventilatsioonile ja hingamissagedusele (I uuring).
3. Analüüsida erineva intensiivsusega sissehingamislihaste soojenduse mõju MIP väärtustele (II uuring).
4. Võrrelda submaksimaalsel sõudmisel sõudeergomeetril spetsiifilise sissehingamislihaste soojenduse ja traditsioonilise sõudjate soojenduse mõju maksimaalse hapnikutarbimise aeglasele ja kiirele komponendile (III uuring).

Materjal ja meetodid

Käesolev doktoritöö põhineb neljal erineval uuringul (Tabel 1). I ja III uuring viidi läbi kõrgel rahvusvahelisel tasemel võistlevatel Eesti sõudjatel uurimaks spetsiifilise sissehingamislihaste soojenduse mõju submaksimaalsele sooritusvõimele sõudeergomeetril, millele lisaks analüüsiti mõjusid ka maksimaalse hapnikutarbimise aeglasele ja kiirele komponendile. II uuring viidi läbi kehaliselt aktiivsetel noortel meestel, et võrrelda erineva intensiivsusega sissehingamislihaste soojenduse mõju MIP väärtustele. Sissehingamislihaste soojendust teostati PowerBreathe® K-1 digitaalsel seadmel. Vaatlusalused olid sissehingamislihaste soojendust tehes istuvas asendis, ninaklapp võimaldas hingata ainult läbi suu. Vaatlusalused pidid PowerBreathe seadme vedru takistusele hingama sisse maksimaalselt kiirelt ja sügavalt ning seade hoidis automaatse helisignaaliga kahe hingamistsükli vahet 4,5 sekundit, et vältida pearingluse teket.

Kõik uuringud olid kooskõlastatud Tartu Ülikooli inimuuringute eetikakomiteega.

Tabel 1 Käesoleva doktoritöö uuringutes osalenud uuritavate arv ja antropomeetrilised andmed.

	Eeluuring (avaldamata andmed) (kõrgel tasemel meessõudjad)	**I, III uuring** (kõrgel tasemel meessõudjad)	**II uuring** (kehaliselt aktiivsed mehed)
Uuritavate arv (n)	12	10	10
Vanus (a)	20.0±2.9	23.1±3.8	26.4 ± 4.1
Kehapikkus (cm)	185.0±6.9	188.1±6.3	183.3 ± 5.5
Kehakaal (kg)	81.3±8.62	85.6±6.6	83.7 ± 7.8

Järeldused ja kokkuvõte

Uuringute põhjal tehti järgmised järeldused:

1. Spetsiifiline sissehingamislihaste soojendus intensiivsusel 40% MIP ei paranda statistiliselt oluliselt sõudjate sooritusvõimet, kuid võib tõsta hingamissagedust sissehingamislihaste soojenduse järgselt.
2. Sissehingamislihaste soojendus 40% ja 60% MIP muutsid statistiliselt oluliselt MIP väärtusi. Soojendus intensiivsustel 15% ja 80% MIP seda aga ei teinud.
3. Sissehingamislihaste soojenduse lisamine sõudjate tavasoojendusele ei mõjutanud statistiliselt oluliselt hapnikutarbimise aeglast või kiiret komponenti submaksimaalsel töövõime testil.

Kokkuvõttes võib käesoleva doktoritöö uuringute põhjal öelda, et spetsiifiline sissehingamislihaste soojendus intensiivsusel 40% MIP ei parandanud sõudjate submaksimaalset sooritusvõimet ega ka hapnikutarbimise dünaamikat. Kõikides varasemates uuringutes on kasutatud just 40% MIP intensiivusust soojenduses, kuid meie uuringud tõid välja, et paremini võiks sobida kõrgem intensiivsus 60% MIP, mis vajaks edasisi uuringuid nii sõudjatel kui ka teistel vastupidavusalade esindajatel.

Praktiline väärtus

Sõudmine on väga intensiivne spordiala, mille võistlus- ja treeningkoormuste mõju sportlase erinevate organsüsteemide funktsioneerimisele on suur. Üheks lisavõimaluseks sõudjate treeningutele on hingamislihaste spetsiifiline treening ja soojendus. Kuna sõudmises on sportlase kehaasend tõmbetsüklis rindkere liikuvust takistav ehk diafragma ja hingamislihaste töö on raskendatud võib väsimus tekkida varem. Spetsiifilise sissehingamislihaste treenimise, treening- ja võistluseelse sissehingamislihaste soojenduse ja treeningu või võistlusjärgse lõdvestuse lisamine olemasolevatele meetoditele oleks kindlasti lisaväärtus hingamislihaste väsimuse edasi lükkamiseks, mis võiks aidata sooritusvõime paranemisele kaasa.

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2014–2016	University of Tartu teaching assistant in physiotherapy education.
2011–....	University of Tartu: PhD studies in Exercise and Sport Sciences;
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Supervised master thesis projects

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„Alaseljavalude esinemine ja seda põhjustavad tegurid Eesti sõudjate seas.“ Jaanus Akel (2015);

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„Alajäseme ülekoormusvigastuste riskitegurite hindamine Eesti noorkorvpalluritel.“ Liis Toomsalu (2016).

„Alajäsemete ülekoormusvigastuste riskifaktorite levimus Eesti noortel naiskorvpalluritel ühe naiskonna näitel.“ Liis Sepp (2017)

„Hooajaeelne õlaliigese sise- ning välisrotaatorlihaste isomeetrilise ja ekstsentrilise maksimaalse tahtelise kontraktsioonijõu hindamine dünamomeetri näidu alusel ujujatel ja võrkpalluritel tuvastamaks kõrgendatud õlavigastuste riskiga sportlasi.“ Taavi Turban (2017).

„Alaselja ja alajäseme piirkonna ülekoormusvigastuste registreerimine Eesti kergejõustiklastel 12-nädalase suvise treeningperioodi vältel.“ Hanno Tikkerbär (2017).

„Nordic Hamstring harjutusprogrammi kasutus reie tagakülje lihaste vigastuste ennetuses Eesti meistri- ja esiliiga jalgpalliklubide seas 2016–2018 hooaegadel.“ Karel Kübar (2019).

Publications

Arend, M., Mäestu, J., Kivastik, J., Rämson, R., Jürimäe, J. (2015). Effect of inspiratory muscle warm-up on submaximal rowing performance. *Journal of Strength & Conditioning Research* 29(1), 213–8

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Juhendatud magistritööd

„Laborivälised testid aitavad tuvastada alajäseme ülekoormusvigastuste riskitegureid kergejõustiklastel.“ Maarja Kalev (2015).

„Kinesioteibi akuutne mõju funktsionaalsetele näitajatele hüppeliigese kroonilise ebastabiilsuse korral.“ Ivar Vähi (2015).

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DISSERTATIONES KINESIOLOGIAE UNIVERSITATIS TARTUENSIS

1. **Lennart Raudsepp.** Physical activity, somatic characteristics, fitness and motor skill development in prepubertal children. Tartu, 1996, 138 p.
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