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

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Supervisor: Professor Mati Pääsuke, PhD
Institute of Sport Sciences and Physiotherapy,
Faculty of Medicine, University of Tartu, Tartu, Estonia

Opponent: Professor Arvydas Stasiulis, PhD
Department of Health Promotion and Rehabilitation,
Lithuanian Sports University, Kaunas, Lithuania

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CONTENTS

ABBREVIATIONS

BMC	Bone mineral content
BMD	Bone mineral density
BMI	Body mass index
CT	Twitch contraction time
DXA	Dual energy X-ray absorptiometry
HRT	Twitch half-relaxation time
KE	Knee extensor
MPF	Mean power frequency
MVC	Maximal voluntary contraction
PAP	Post-activation potentiation
PF	Peak force
RFD	Twitch maximal rate of force development
RPM	Revolution per min
RR	Twitch maximal rate of force relaxation
sEMG	Surface electromyography
VO_{2max}	Maximum oxygen consumption
W_{peak}	Peak power output

LIST OF ORIGINAL PUBLICATIONS

I Lepasalu, L., Ereline, J., Gapeyeva, H., & Pääsuke, M. (2018). Changes in knee extensor muscle contractile properties after cycling at constant intensity. *Medicina dello Sport*, *71*(3), 323–335. https://doi.org/10.23736/S0025-7826.18.03323-9

II Lepasalu L., Ereline J., & Pääsuke M. (2023). The relationship between bone parameters, body composition, and lower extremity strength in road cyclists. The *Journal of Sports Medicine and Physical Fitness, 63*(11), 1182–1187. https://doi.org/10.23736/S0022-4707.23.15067-5

III Lepasalu, L., Ereline, J., Reinvee, M., & Pääsuke M. (2024). Seat pressure asymmetries after cycling at constant intensity. *Symmetry*, *16*(3), 270. https://doi.org/10.3390/sym16030270

Paper I, II and III. Laura Lepasalu had primary responsibility for leading the design of the studies, coordinating and implementing data collection, performing statistical analyses, and writing the manuscripts.

1. INTRODUCTION

Cycling is an endurance sport where athletes are required to train intelligently and consistently to manage fatigue levels (Decorte et al., 2012; Lepers et al., 2008; Theurel & Lepers, 2008). As endurance athletes compete in international competitions, they constantly seek improvements to maintain performance despite the development of fatigue, with primary purpose of avoiding injuries, including those from asymmetric muscle loading (Albero et al., 2023; De Almeida Azevedo et al., 2022; Girard et al., 2013).

Traumatic and overuse injuries are very common in cycling, with up to 85% of cyclists developing one or more overuse injuries during their careers (Dettori et al., 2006). For example, approximately 23 million cyclists develop at least one overuse injury during their career in the United States alone (Dettori et al., 2006). About 51.5% of cycling injuries result from overuse (Barrios et al., 2015; De Bernardo et al., 2012). While fatigue is inevitable, it can be delayed, so neuromuscular functional ability is enhanced (Abbiss & Laursen, 2005).

The primary muscles working during cycling are the muscles of the lower extremity (Chapman et al., 2006), and the fatigue of these muscles determines the sitting position of a cyclist after prolonged exercise. It is widely known that constant sitting while working in front of a computer requires breaks to avoid musculoskeletal problems, but it is less recognized that constant exercise and sitting in the saddle could result in similar patterns in daily life, even though cyclists actively adjust their position in the saddle. As a result, the existing muscle activation pattern is automatically modified when cyclists become fatigued during cycling, resulting in a change in muscle activity (Balasubramanian & Jayaraman, 2009; L. Wang et al., 2018). This can eventually lead to several injuries associated with muscle overload injuries and even negatively impact body posture after cycling exercise (Rooney et al., 2020; Visentini et al., 2022). Several studies have shown changes in muscle activity in cycling, but little is known concerning cyclists' posture before and after exercise (Bini et al., 2014; Bini & Hunter, 2021).

Although many studies have reported that success in cycling is primarily determined by physiological endurance variables such as maximum oxygen consumption (VO_{2max}) or critical power, ventilatory threshold and exercise economy (Hopker et al., 2017; van der Zwaard et al., 2019), long-term cycling exercise (more than 30-min) can alter athletes' neuromuscular performance, which is attributed to alterations in the peripheral and central nervous system (Decorte et al., 2012; Gandevia, 1998). Several previous studies have demonstrated that a reduction in knee extensor (KE) muscles (*m. quadriceps femoris*) maximal voluntary contraction (MVC) force occurs due to changes in both central and peripheral processes after prolonged cycling (Kordi et al., 2021; Lepers et al., 2008; Thomas et al., 2016). However, there is a lack of information regarding the contractile properties of muscles after exercise, including post-activation potentiation (PAP) (Garzia, 2013).

Another relevant factor that influences fatigue development in cyclists is their body composition and anthropometric parameters. Although cyclists cannot change their anthropometric parameters, examining the relationship between muscle strength and postural changes, assessed by sitting contact area distribution and by pressure right-to-left ratio, could provide valuable information on the prevention of overload problems. There is no doubt about the importance of mechanical loading of the skeletal system for bone mass development and maintenance (Campion et al., 2010; Olmedillas et al., 2012). Cycling as a non-weight-bearing sport does not stimulate bone mass gradual growth (Martínez-Noguera et al., 2023; Olmedillas et al., 2012; Smathers et al., 2009). Studies have shown that long-term adaptation to cycling reduces fat percentage, bone mineral content (BMC), and bone mineral density (BMD), while also increasing the voluntary force-generation capacity of KE muscles (Hilkens et al., 2023; Kordi et al., 2021; Olmedillas et al., 2011). It is still unclear whether higher muscle functional capacity, determined by the force of isometric voluntary contraction of KE muscles, is related to bone mineral parameters and body composition.

The primary aim of the doctoral thesis was to examine the changes in muscle contractility and sitting contact area distribution following constant-intensity cycling, as well as the relationship between lower extremity strength, body composition, and bone mineral parameters in highly trained male road cyclists.

2. LITERATURE REVIEW

2.1. Characterization of constant intensity cycling exercise

Constant intensity cycling exercise is widely used in the evaluation of physiological and functional performance in cyclists (i.e., pursuit on track, time trial), but it is also popular in rehabilitation (Du Plessis et al., 2022; Thomas et al., 2016). In most cases, cyclists are unaware of the reasons why they choose a particular pedalling rate or they believe that this rate should be maintained regardless of changes in power output (Lepers et al., 2000; O'Malley et al., 2024).

Generally, athletes prefer different intensities of cycling, but constant intensity cycling is performed indoors on a fixed ergometer before rehabilitation or strength training, while cyclists' own bicycles are used for outdoor training (Holliday et al., 2023; Lipski et al., 2022). Also, time trials on flat courses are performed mainly at constant intensity (Lipski et al., 2022). Cycling at constant intensity is therefore more common among road cyclists since off-road cyclists use different terrains with variable intensity. Furthermore, the intensity of both disciplines can also vary depending on external conditions (such as hills, weather conditions, technical bike courses). As workload increases, cyclists must exert more power to maintain a constant pedalling speed (Kordi et al., 2018; MacIntosh et al., 2000). Lepers et al. (2008) study indicated that cycling at a variable power output induced a similar magnitude of neuromuscular fatigue as cycling at a constant intensity.

Indoor cycling is characterized by high involvement of skeletal muscles and cardiovascular system (De Melo Dos Santos et al., 2017). Chavarrias et al. (2019) systematic review showed that indoor cycling may be effective for enhancing VO_{2max} and lean body mass, and also for reducing body fat mass, systolic and diastolic blood pressure. In addition, neuromuscular fatigue has been assessed during and after constant load cycling by a few authors (Decorte et al., 2012; Lepers et al., 2008; Thomas et al., 2016).

2.2. Bone and body composition parameters of male road cyclists

Studies on cycling have not demonstrated a positive relationship between bone health and cycling exercise (Martínez-Noguera et al., 2023; Olmedillas et al., 2012; Smathers et al., 2009). The development of bone health problems in cyclists can be influenced by a number of factors. Athletes regularly evaluate changes in body composition to determine the effectiveness of training and nutritional interventions (Pimentel et al., 2019; van de Wiel & Verstappen, 2018).

One way to delay fatigue on long climbs is to decrease cyclist body mass because lighter cyclists expend less energy to maintain the same speed on uphill terrain compared to heavier riders (Martínez-Noguera et al., 2023). This energy deficit could lead to poor nutrition affecting their performance, as well as overall and bone health. Moreover, a lack of loading due to the mode of exercise could negatively affect bone health. Therefore, it is essential to monitor cyclists' bone health.

A variety of practical methods are used in professional sport to assess body composition, including dual energy X-ray absorptiometry (DXA), skinfolds, bioelectrical impedance analysis, and air displacement plethysmography (Buehring et al., 2014). Studies have confirmed that the DXA method can be used for estimating total body composition, BMD, and BMC in high-level cyclists (Alejo et al., 2022; Baker & Reiser, 2017). There is an association between improvements in physical function and improvements in body composition and body mass index (BMI) (Hanson et al., 2009; Park et al., 2019).

BMD and BMC are significant determinants of skeletal health (Baker & Reiser, 2017; Medelli et al., 2009). Various types of exercise have different osteogenic effects (Platen et al., 2001). While weight-bearing activities result in higher BMD, cycling as a non-weight-bearing sport has minimal external loading and is labelled as a non-osteogenic sport (Martínez-Noguera et al., 2023; Olmedillas et al., 2012; Smathers et al., 2009). Hilkens et al. (2023) showed that low BMD is highly prevalent in advanced career male elite cyclists and may not fully recover after the professional cycling career. In addition, low BMD is associated with low BMI, fracture incidence, lack of bone-specific physical activity, and low energy availability in active career elite cyclists (Hilkens et al., 2023). It is interesting to note that already only one season of professional cycling affects bone health status negatively (Martínez-Noguera et al., 2023). Pimentel et al. (2019) compared asymmetries in the lower body between competitive cyclists and non-cyclists and showed that functional asymmetries during cycling are variable; cyclists had increased lower body lean mass and BMD asymmetries compared to non-cyclists. On the other hand, Duncan et al. (2002) found similar BMD values for the whole body, lumbar, femoral neck and extremities in female cyclists compared to sedentary controls.

Cyclists are at risk of developing bone problems, including lower BMC values, from a young age (González-Agüero et al., 2017). Therefore, it is important to reach high BMC values during the first decade of adulthood. Studies comparing differences in the BMC in total or any regional site between adolescent cyclists and non-athlete controls have found higher variation in over 17-year-old participants (Olmedillas et al., 2011).

2.3. Neuromuscular performance characteristics in male road cyclists

Muscle fatigue is a complex phenomenon that sport science defines as the reduction in the maximum force a muscle can exert or by the inability to maintain the required power (Edwards, 1981). Muscle fatigue is caused by both central and peripheral mechanisms, originating from sites located proximal or distal to the neuromuscular junction (Gandevia, 2001). Fatigue in the central nervous system occurs when mechanisms proximal to motor neurons fail, which inhibit signals from the neuromuscular junction to the neurons (Gandevia, 2001). The peripheral fatigue mechanism originates within the muscle fibres themselves (Enoka & Stuart, 1992; Gandevia, 2001). Cycling performance, which is largely determined by muscular power production, can be predicted by MVC (Douglas et al., 2021; Kordi et al., 2018). Studies have demonstrated that changes in central and peripheral processes result in a reduction in KE muscle MVC force after prolonged cycling (Lepers et al., 2000; Millet & Lepers, 2004; Sarre & Lepers, 2005). According to Thomas et al. (2016), central and peripheral processes contribute differently to fatigue after constant-load cycling exercise. Their study showed that with longer exercise durations and lower intensities, central fatigue is exacerbated, while peripheral fatigue is greater at higher intensities and shorter durations. It has been demonstrated that muscles with more slow twitch fibres are more resistant to fatigue than muscles with fast twitch glycolytic fibres (Segerström et al., 2011).

Studies on concurrent aerobic and strength training have repeatedly reported that muscle strength is crucial to cycling performance (Kordi et al., 2020; Segerström et al., 2011). Increased power-generating capacity has been linked to a larger proportion of muscle mass (Kordi et al., 2018). As revealed by studies, cycling performance depends on achieving high power output on a long-term basis (Rønnestad et al., 2015; Sunde et al., 2010). Maximal strength is positively associated with cycling performance, especially in short-duration efforts (Kordi et al., 2018, 2021). Research has pointed out that differences in body composition and size can influence both maximal strength and power generation capacity (Jaric, 2002).

Nonetheless, the understanding post-exercise of muscle contractile properties, including PAP, remains unclear. PAP refers to an acute enhancement of performance characteristics due to their contractile history (Boullosa et al., 2018). PAP has been mostly investigated in power-demanding sports, such as sprints, throws, and jumps, but only some studies have observed PAP in endurance athletes following MVCs (Boullosa et al., 2018; Doma et al., 2018; Gołaś et al., 2016).

Prolonged cycling at constant intensity has influence on the neuromuscular system, affecting the pattern or efficiency with which the contractile machinery is activated (St Clair Gibson et al., 2001). Additionally, metabolic changes in recruited fibres can decrease skeletal muscle force-generating capacity by altering the excitation-contraction coupling process during prolonged exercise (St Clair Gibson et al., 2001).

Neuromuscular fatigue is commonly assessed shortly after exhaustion, but few studies have examined fatigue development during exercise (Lepers et al., 2000, 2008; Sarre & Lepers, 2005). Long-term adaption to cycling is associated with greater voluntary force-generation capacity of KE muscles than controls (Kordi et al., 2021; Sachet et al., 2022). Rectus femoris from the quadriceps muscles group produces around 39% of the total positive mechanical work during cycling exercise (Ericson M., 1986; Hug & Dorel, 2009). Thus, it is a fact that sEMG signals of rectus femoris and other quadriceps femoris muscles are expected to increase significantly with the increase in cycling workload (Bing et al., 2024). In addition to KE muscles, most of the total positive mechanical work (27%) is done by knee flexor muscles like biceps femoris, semitendinosus and semimembranosus (Ericson, 1986). Bing et al. (2024) found no change in sEMG signals of the tibialis anterior and medial gastrocnemius muscles and explained it by these muscles' duties in cycling – period of activation and smaller muscle sizes. To take it all into account, it can be assumed that muscles like rectus femoris and biceps femoris might develop muscle strains easily during high-workload cycling exercise (Bing et al., 2024). Kordi et al. (2017) found significant relationships between the knee flexors and hip extensors and also between maximal cycling power and the maximal isometric torque of the KE muscles. The study by Priego et al. (2014) pointed out that muscle fibre recruitment patterns changed with the increase in cycling workload. While slow-twitch muscle fibres are used during low-intensity cycling, more and more fast-twitch muscle fibres are also recruited to generate more power with the increase in the workload (Tesch & Wright, 1983). This leads to an increase in the amplitude of sEMG signals because fast-twitch muscle fibres have a higher firing rate (Gandevia, 2001).

In high-level cyclists, a number of physiological parameters have been used to predict performance: VO_{2max}, maximum (W_{peak}) and relative power output, absolute and relative power output at ventilatory thresholds 1 and 2, as well as cycling efficiency (Denham et al., 2020; Lucía et al., 2001; MacDougall et al., 2022). Less attention has been paid to neuromuscular fatigue during endurance exercise that can provide significant knowledge about the improvement of an athlete's performance, and studying changes occurring in the muscle (e.g., twitch contractile properties) during cycling exercise can add valuable information to this issue (Boullosa et al., 2018).

Previous studies have shown that absolute power output is the primary performance factor on flatter terrain in addition to aerodynamic drag (Millet & Candau, 2002). Absolute power output relates proportionally to the rider's body mass, while relative power output inversely relates to the cyclist's body mass (Pringle et al., 2011). Cycling workload is also measured in watts and can be controlled by selecting the right gear ratio or pedal power level (Bing et al., 2024). There has been research showing how pedal power level affects sEMG signals of the main lower limb muscles (Carpes et al., 2011; Diefenthaeler et al., 2012).

2.4. Assessment of neuromuscular fatigue and seat pressure asymmetries in cycling

Surface electromyography has been extensively investigated to identify neuromuscular fatigue (Lepers et al., 2000). It is known that muscle fatigue is accompanied by increased integrated electromyogram and decreased mean power frequency (MPF) of electromyogram for a given activity (Edwards, 1981). Surface electromyography represents the sum of the electrical activities of many active motor units in the muscle recorded by placing electrodes on the skin overlying the muscles (Balasubramanian & Jayaraman, 2009). An analysis of the spectral MPF, defined as the frequency that divides the power spectrum into two regions with equal power, has been used to determine the MPF of motor unit action potentials during short-duration muscle contractions in human skeletal muscle (Wang et al., 2018).

A number of studies have shown that cyclists adjust their muscle activation patterns during fatigue (Dingwell et al., 2008; Verma et al., 2016). The study by Sarre et al. (2003) observed that the sEMG signals of the vastus medialis, vastus lateralis, and rectus femoris changed significantly when cycling workload was increased from 60 to 100% of maximum aerobic power. It has also been shown that cycling position influences the synergy between different muscle groups of lower limbs to optimize pedalling efficiency and evaluate the correct cycling position; therefore, proper bike fitting is essential (Millour et al., 2023). The study on the effects of cycling workload and saddle height on muscle activation and coordination patterns of key lower limb muscles revealed that the muscle activation of the rectus femoris and biceps femoris increased with increasing cycling workload, while the medial gastrocnemius activation increased with higher saddle height (Bing et al., 2024).

Cyclists tend to prefer using one side of their body during cycling (Carpes et al., 2010). Research has shown that cyclists adjust their body positions when fatigue occurs (Dingwell et al., 2008; MacIntosh et al., 2000; Verma et al., 2016), and it should be more relevant to high-level cyclists compared to recreational cyclists. Rannama & Port (2015) indicated that during 30 s of maximal intensity cycling, there were leg dominance-dependent asymmetries in pedalling power patterns. A lateral preference in cycling may result in bilateral asymmetry, leading to increased injury risks (Carpes et al., 2010). Moreover, cycling-related overuse injuries may arise due to excessive mechanical stresses exerted on the musculoskeletal system, influenced by body positioning and training intensity (Bini & Hunter, 2021; De Bernardo et al., 2012; Visentini et al., 2022). Several studies have demonstrated that typical overuse injuries in cycling cause saddle sores, nerve compressions, back, neck, knee, ankle, and/or foot pain (De Bernardo et al., 2012; Rooney et al., 2020; Visentini et al., 2022). The prevalence of knee and lower back pain has been comparable among competitive road cyclists and recreational cyclists (Clarsen et al., 2010). Therefore, the findings of this study would also be valid for recreational cyclists who do not have similar exercise adaptation to athletes.

However, the question is whether there is asymmetry in pressure under the ischial tuberosity or the gluteal area after cycling exercise. Measuring pelvic anthropometric parameters helps researchers understand the dimensions of ischial tuberosities and the pressure beneath them. It is, therefore, essential to learn how to prevent non-traumatic cycling-related injuries as well as increase public awareness and health among cyclists. A number of recommendations have been made for reducing these non-traumatic cycling injuries, including altering the bicycle fitting or technique, or simply taking adequate rest (Holliday & Swart, 2022; Yum et al., 2021). However, there are also specific techniques for reducing discomfort in riders' buttocks when cycling, for example, measuring the distance between the two ischial tuberosities to determine the seat size (Chen, 2018; Goossens et al., 2005). According to research, ischial tuberosities' sensitivity to pressure varies with the size of their contact area (Chen, 2018; Goossens et al., 2005).

Regardless of how ergonomic the bicycle's saddle or seated position is, sitting in the saddle for long periods of time without breaks is detrimental to the human body and muscles (Bressel et al., 2007, 2010; Bressel & Larson, 2003). It is known that sitting increases pressure under the ischial bones, consequently restricting blood flow to the tissues and possibly resulting in pain or discomfort (Johnson & Varacallo, 2024). Injuries to the ischial tuberosity are strongly correlated with bicycle seat pressure (Bressel et al., 2010; Dettori & Norvell, 2006). The measurement of seat pressure distribution is one method used to study the effects of long-term sitting. Research suggests that high spinal load, which can cause lower back pain, is closely related to high pressure at the ischial tuberosities (Makhsous et al., 2009; Srinivasan & Balasubramanian, 2009). The measurement of seat pressure distribution is an objective and reliable method for assessing subjective discomfort ratings (De Looze et al., 2003). Changes in seat pressure distribution could predict overuse injuries (Clarsen et al., 2010; De Bernardo et al., 2012; Visentini et al., 2022).

There have been numerous studies about seat pressure during cycling (McDonald et al., 2022; Verma et al., 2016; Vicari et al., 2023), but no study has evaluated the relationship between pelvic anthropometric parameters, muscle activity, and seat pressure variables before and after cycling exercise at constant intensity.

2.5. Summary of the background

Considering the influence of constant cycling exercise, there is limited scientific literature on the contractile properties of cyclists' muscles and posture before and after constant intensity exercise. Moreover, there is still no clear understanding of the relationship between the isometric MVC force of KE muscles and bone mineral parameters, as well as body composition. Furthermore, there is no clear evidence regarding bilateral asymmetry and its impact on seat pressure distribution following constant load cycling exercise.

3. AIMS OF THE STUDY

The aim of the current thesis was to analyse body composition, muscle strength characteristics, and adaptation to constant intensity cycling exercise in male road cyclists.

According to the general aim, the specific objectives of the present study were:

1. To evaluate relationships between body composition, bone mineral parameters, and the knee extensor muscle's isometric voluntary strength in male road cyclists and untrained controls (Paper II).
2. To evaluate the changes in knee extensor muscle isometric voluntary strength and electrically evoked twitch contractile properties following 30-min constant load cycling and during a 30-min recovery period under laboratory conditions in male road cyclists (Paper I).
3. To evaluate seat pressure asymmetries after 30 min of cycling exercise at constant intensity under laboratory conditions in association with pelvic anthropometric and neuromuscular fatigue characteristics in male road cyclists (Paper III).

4. MATERIALS AND METHODS

4.1. Participants

In total, 12 male road cyclists and 12 male untrained controls gave informed consent and participated in this study. Table 1 presents the division of participants, training history, mean age, and anthropometric characteristics in different studies. The study included cyclists with a long training history and controls to better understand the benefits of regular exercise. The road cyclists had a training history between 5 and 18 years in cycling sports at a competitive level. Before the study, all the participants completed a questionnaire concerning their personal and medical history. Ten cyclists participated in the first study, and twelve cyclists in the second and third study.

The inclusion criteria for the cyclists were: they had to be registered with the Estonian Cyclists Union in the male Elite or Under-23 categories, they had to have long-term adaptation to cycling and currently competing professionally or as amateurs within Europe; the target group of cycling participants was classified as tier 3 – highly trained/national level in terms of the classification framework (McKay et al., 2022). The recruitment of cyclists was conducted in collaboration with the Estonian Cyclists Union.

The controls included recreationally active young men who did not regularly participate in resistance or endurance training, including cycling. The inclusion criteria for the comparison group of untrained controls in Paper II were: they had not regularly trained or participated in national cycling sport competitions in the preceding year, but could only participate in recreational activities; they were not endurance or resistance trained.

Both groups had to be healthy and reported no musculoskeletal or bone-related injuries during the past six months according to their health questionnaire; and there had to be no use of medications known to adversely affect bone density (e.g., anticonvulsants, corticosteroids). Injuries were not reported by any of the participants during the data collection and the preceding six months.

All the participants were contacted by telephone, they were informed about the details of the experimental procedures, and the possible risks and benefits of the study were discussed.

The participants provided written informed consent and were informed of the study objective and procedures in detail. The study protocol was approved by the Ethics Review Committee on Human Research, University of Tartu (Report nr 217/T-3) in accordance with the Declaration of Helsinki.

Table 1. The mean (± SD) age, anthropometric and performance characteristics and training history of the participants.

Variable	Paper I Cyclists (n=10)	Paper II Cyclists (n=12)	Paper II Controls (n=12)	Paper III Cyclists (n=12)
Age (years)	23.8 ± 3.7	22.8 ± 3.7	23.3 ± 3.2	23.2 ± 3.5
Height (cm)	183.5 ± 7.0	184.3 ± 6.1	180.0 ± 3.5*	185.1 ± 5.5
Body mass (kg)	74.5 ± 6.6	74.3 ± 6.3	81.3 ± 10.6	74.5 ± 6.2
BMI (kg·m^{-2})	22.1 ± 1.7	21.9 ± 1.8	25.1 ± 3.3**	21.8 ± 1.8
VO_{2max} (ml/kg/min)				64.5 ± 4.6
50% W_{peak} (W)				208.0 ± 22.7
Training history (years)	11.2 ± 4.3	9.7 ± 2.8		9.9 ± 2.5

Note: BMI: body mass index; VO_{2max}: maximum oxygen consumption; W_{peak}: peak power output; * significant difference between cyclists and controls on a level of $p<0.05$; ** $p<0.01$.

4.2. Study design

This dissertation is based on two separate controlled experiments (Paper I and III) with one between-group analysis (male road cyclists and male untrained controls, Paper II) under laboratory condition. The present cycling protocol mimicked the protocol used in a previous study that assessed the effect of power output on cycling performance (Theurel & Lepers, 2008). The experimental study design is illustrated in Figure 1. This experimental study was conducted at the University of Tartu in the Laboratory of Kinesiology and Biomechanics. First of all, anthropometric measurements were completed, and the participants filled out a questionnaire concerning their personal health and background.

In Paper I, the cyclists performed indoor cycling exercise at a constant intensity of 250W using their own bicycles fixed to ergometer Tacx Cosmos (Tacx B.V., Netherlands). Additionally, the subjective fatigue rate of the participants was assessed during exercise using the Borg scale and their heart rate was monitored during exercise. The isometric MVC force and twitch contractile characteristics of KE muscles were assessed in a custom-made dynamometric chair before and after the cycling exercise (Pääsuke et al., 1999). The contractile properties of KE muscles were measured using an electrical stimulation technique.

In Paper II and III describe a test where approximately one to two weeks before the laboratory test, all the cyclists performed incremental cycling tests to exhaustion to determine their VO_{2max} and W_{peak}. DXA (Bilsborough et al., 2014; Wang et al., 2013) was used to assess body composition parameters in cyclists and control group participants. Before assessing isometric MVC force, the cyclists' sitting contact area was measured, in addition to pressure, and stability indicators using the ConforMat Research pressure mapping system (ConforMat; Tekscan Inc., Boston, MA, USA). Then the isometric MVC force and twitch contractile characteristics of KE muscles were assessed in a custom-made dynamometric chair in all the participants, including the controls. The cyclists performed indoor cycling exercise at constant intensity at 50% of W_{peak} with sEMG recording the spectral MPF over the erector spine at L3, gluteus medius, biceps femoris, vastus lateralis, and rectus femoris muscles. The control group did not perform the cycling exercise. After the cycling exercise, seat pressure distribution was measured again. The final step in this study was to assess the isometric MVC force and twitch contractile characteristics of KE muscles once again after the exercise in the cyclists.

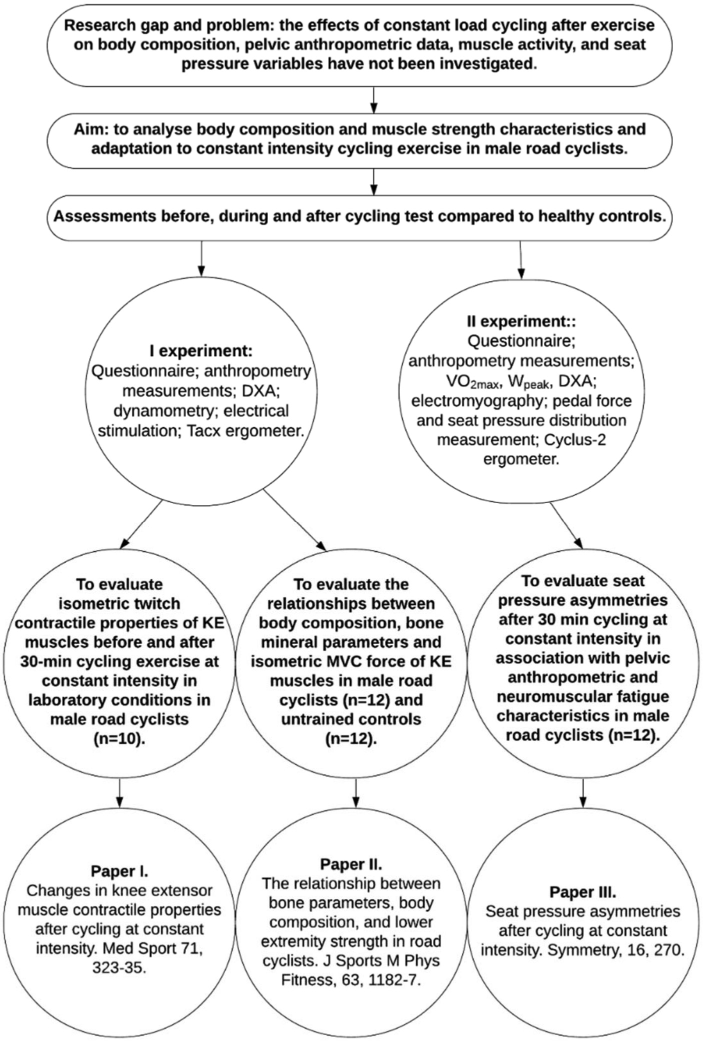

Figure 1. The study design.

Note: VO_{2max}: maximum oxygen consumption; W_{peak}: peak power output; DXA: dual energy X-ray absorptiometry; MVC: maximal voluntary contraction; KE: knee extensor.

4.3. Measurements

4.3.1. Cycling exercise

In Paper I, the cyclists mounted their own race bicycles to the Tacx Cosmos (Tacx B.V., Netherlands) ergometer for cycling exercise. A standardized 5-min warm-up was performed by all cyclists before each test session. The participants were instructed to cycle at 90 ± 5 revolution/min (rpm). Each participant performed one 30-min cycling exercise at 250 W at constant intensity. The heart rate of cyclists was monitored (mod. S725x, Polar Electro Oy, Kempele Finland).

In the experiment described in Papers II and III, all the cyclists performed an incremental cycling test to exhaustion at the Vomax Sports Medicine Center prior to the laboratory testing to determine their VO_{2max} and W_{peak} on an electronically braked cycle ergometer (Corival V3, Lode, Netherlands). The test was conducted by a sports medicine doctor. The testing protocol consisted of a 5 min warm-up at 100 W power level followed by the incremental cycling exercise. The participants were asked to cycle at a comfortable cadence of 90 ± 5 rpm. The starting intensity was 100 W with 25 W power output increments every 2 min until exhaustion. The task was interrupted when the cyclist cadence fell below 70 rpm. The participants were strongly verbally encouraged to exert themselves maximally. Gas samples were automatically collected for every 30 s period in breath-by-breath mode for the oxygen consumption measurement using a portable open circuit spirometry system during an incremental cycling test (MetaMax 3B, Cortex, Leipzig, Germany). Standard software was used to analyse all the data (MetaMax-Analysis 3.21, Cortex, Leipzig, Germany). VO_{2max} and W_{peak} were determined. The following analyses included cycling exercise intensity described as 50% of W_{peak}.

The participants performed 30-min cycling exercise at 50% W_{peak} at constant intensity on a Cyclus-2 ergometer (Avantronic, Cyclus 2, Leipzig, Germany) (Figure 2). The cyclists used their own cycling shoes, pedals, and racing bicycles. Prior to the testing session, the participants performed a standardized warm-up consisting of 5-min of cycling at constant intensity of 100 W. The participants were instructed to cycle at 90 rpm.

[redacted] [redacted]

Figure 2. Experimental setup for the cycling test at constant intensity at 50% W_{peak} (Paper III).

4.3.2. Anthropometry

The anthropometric measurements assessed were body mass and height by Martin metal anthropometer (± 0.1 cm) and clinical scales (± 0.05 kg), and BMI was calculated (kg/m^2). These assessments were performed after the participants completed a health and history questionnaires.

4.3.3. Dual energy X-ray absorptiometry

The radiology measurements of the whole body were obtained at Chemicum, University of Tartu, using a DXA machine (Lunar Corp., Madison, WI, USA) (Bilsborough et al., 2014; Wang et al., 2013). Prior to positioning the participant on the DXA table, all plastic and metal objects were removed from their clothing. The participants were scanned lying on their backs with their hands at their sides, following the manufacturer's instructions. Body and leg fat % were calculated based on whole-body mass (kg), body lean and fat mass (kg), body and leg BMD and BMC, leg lean and fat mass (kg), and regional BMD and BMC. Lean mass and BMC were expressed in terms of mass (kg) and BMD as mass/area (g/cm^2). The size of the ischial tuberosity, the pelvis height, and the pelvis width were measured (Figure 3). The analyses of the scans were performed using the manufacturer's software (Version 1.91). All the interpretations were performed by the same experienced physician.

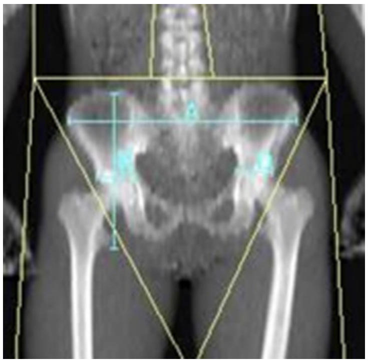

Figure 3. Assessment of pelvis height, width and ischial tuberosity size of male road cyclists using a DXA machine.

4.3.4. Dynamometry

A custom-made dynamometric chair was used to measure the isometric MVC forces of the KE muscles before and after exercise (Figure 4) (Pääsuke et al., 1999). The participants sat with an angle of 110° at the hip and 90° at the knee during the measurement. Three Velcro belts were placed over the chest, hips, and thighs of the participant to secure their body positions. The unilateral knee extension force was measured by a strain gauge transducer (DST 1778, Russia) fixed to a chair and connected to a rigid bar that was attached to the plate. A strain gauge transducer pad was placed on the anterior aspect of the leg approximately 3 cm from the apex of the lateral malleolus. The strain-gauge transducer provided linear signals from 0 to 2500 N. A frequency of 1 kHz was used to capture the force signals, and these signals were stored on computer hard drives using the software WinSportlab (Urania, Ltd, Estonia).

Repeated static loads on the plate were used to calculate the reproducibility of the force measurements. There was a relative error of less than 1% between the trials and a relative difference of less than 0.7% between the trials (Requena et al., 2008). Based on a previous study, test-retest correlations with a 5-day interval between the measurements were r=0.92, demonstrating high reliability of isometric MVC force measurements using a strain gauge transducer (Raudsepp & Pääsuke, 1995). The participant was instructed to extend the dominant leg against the cuff-fixed strain-gauge system as forcefully as possible for 2–3 s during the measurement of isometric MVC force. An individual's dominant leg was determined by their preference for kicking. The participants were motivated by visual and verbal feedback. A maximum of two attempts was recorded with a recovery period of 60 s between trials, and the best result of the isometric MVC force was taken for further analysis. Isometric MVC force was measured before and after a 30-min cycling exercise, as well as during the recovery period (15 min and 30 min after the exercise).

Figure 4. Experimental setup for the measurement of the isometric maximal voluntary contraction force of the KE muscle with electrical stimulation electrodes located in the appropriate locations.

4.3.5. Electrical stimulation

In order to measure twitch contraction characteristics, the participants sat in a custom-made dynamometric chair in which the participants' body position was the same as described for measuring the isometric MVC force of KE muscles

(Figure 4). Percutaneous nerve stimulation induced electrically evoked twitches in the KE muscles of the dominant leg. A surface electrode (2 mm thick) was used along with a self-adhesive electrode (Medicompex SA, Ecublens, Switzerland). The contact surface was prepared by applying electrode gel and rubbing the underlying skin with isopropyl alcohol before attaching the electrodes. A cathode (5 x 5 cm) was placed on the skin over the femoral nerve in the inguinal crease, while an anode (5 x 10 cm) was placed over the midportion of the thigh. Electrical stimulation was delivered with rectangular pulses of 1-ms duration, applied at supramaximal intensity (130–150V) from an isolated voltage stimulator (DG2A, Digitimer Ltd., UK). When twitch force failed to increase despite additional increases in stimulation intensity, the voltage of rectangular electrical pulse was progressively increased to determine the supramaximal stimulation intensity. Further twitch measurements were performed using a stimulation intensity 20–30% greater than that needed for maximal twitch response. For further analysis, the trial with the highest peak force (PF) of two maximal twitch contractions was chosen in relaxed muscle. Between the twitches, there was a 60 s rest period. Immediately within 2 s following the onset of relaxation, a potentiated twitch was observed.

During twitch contraction, the following characteristics were computed:

1. Twitch contraction time (CT) – the time between the onset of a contraction and the onset of a twitch.
2. Twitch PF – highest value for isometric force production.
3. Twitch half-relaxation time (HRT) – time it takes for a twitch PF to fall to half its maximum.
4. PAP – the percentage increase in potentiated twitch PF compared to rest.
5. Twitch maximal rate of force development (RFD) – the first derivative of force development (dF⁄dt).
6. Twitch maximal rate of force relaxation (RR) – the first derivative of the decline of force (-dF⁄dt).

4.3.6. Electromyography

During the cycling test at constant intensity, sEMG was recorded bilaterally from the erector spinae at L3, gluteus medius, biceps femoris, vastus lateralis, and rectus femoris muscles using an electromyograph ME6000 (Kuopio, Finland). T-601 surface electrodes were used to record sEMG activity. The skin under the electrodes was shaved, abraded, and soaked in alcohol for proper cleaning. Conductive gel was applied to the skin to ensure good signal transfer. The electrodes were placed according to SENIAM guidelines (Hermens et al., 2000). The ten electrode positions were marked with ink to ensure reliable electrode replacement. The electrode wires were attached to the skin with adhesive tape to prevent shifting. Raw EMG signals were amplified, digitized and acquired using the PC software MegaWin (Mega Electronics, Kuopio, Finland) at a sampling rate of 1 kHz.

Surface electromyography signals were band-pass filtered at 5–500 Hz using a 4th-order zero-phase-shift Butterworth filter and divided into every 3-second epochs. For each epoch, MPF was calculated based on Fourier Transform (Wang et al., 2018). An electromyograph was used to record the MPF of the measured muscles twice: at the beginning (0–1-min) and at the end (29–30-min) of exercise.

4.3.7. Seat pressure distribution measurement

A pressure mapping device was installed on a table sized 618.5 mm in width, 539.2 mm in length, and 0.762 mm in height. Measurements were recorded before and after the cycling exercise on ConforMat (Tekscan Inc., Boston, MA, USA) (Figure 5). 1024 pressure-sensitive elements were installed in this device, each measuring 14.7 mm x 14.7 mm and arranged in a 32x32 matrix. Adhesive tape was used to fix the pressure mapping device to the table.

In the initial seat position, the hips and knees were bent 90°, and the thighs were in contact with the pressure map with the arms crossed (Figure 5). The participants were asked to sit continuously for 1 min and they were not supported by a backrest. A pressure mapping device was divided into four horizontal regions (right and left femoral, right and left gluteal), allowing for a description of pressure distributions in each region (Figure 6).

Seat pressure distribution data was collected using a seat pressure mat with software (ConforMat Research, version 7.10c, Tekscan Inc.) throughout a 1-min period at a frequency of 5 Hz. Calibration was conducted according to the manufacturer instructions using a linear method. The auto-adjust sensitivity option was selected. The seat pressure distribution was determined through the following variables:

1. The length of the centre of pressure (COP) trajectory (cm) to assess sitting stability.
2. Mean pressure (N/cm^2) and distribution of contact area (%) of the right and left femoral, and right and left gluteal parts. The relative contact area was divided into four parts based on the COP coordinates.
3. Peak pressure (N/cm^2) around the ischial tuberosity on a 3.2 cm^2 area.
4. Peak pressure right-to-left ratio (N/cm^2).

The seat pressure mapping sensor calculated these values between its four most adjacent sensing elements. The ratio was calculated by dividing the right side's pressure by the left side's pressure. Sitting asymmetrically between the left and right sides was indicated by pressure right-to-left ratio.

Figure 5. Cyclist's position on the table during the assessment of seat pressure distribution using a pressure mapping device.

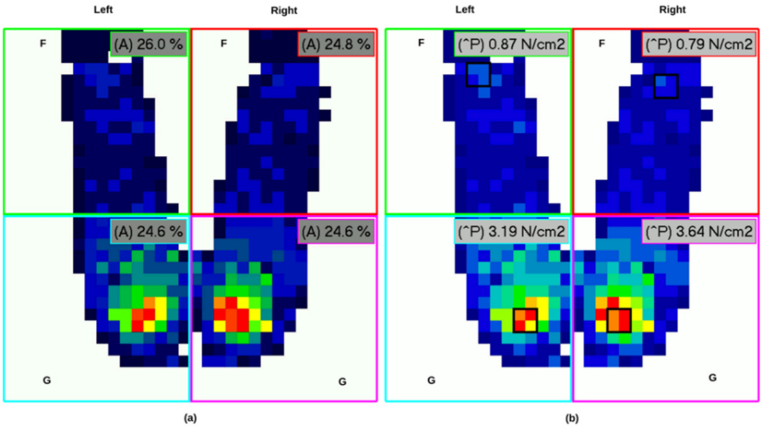

Figure 6. Pressure mapping illustrates the distribution of contact area in four horizontal regions (right and left femoral (F), and right and left gluteal (G) parts) after exercise in one participant. The distribution of contact area is shown in two ways: (a) % distribution of contact area and (b) distribution of contact area in N/cm^2. Red indicates the peak pressure area, while orange, yellow, green, blue and black indicate decreasing pressure areas.

4.4. Statistical analysis

Data analysis was performed using Statistica software for Windows (Statistica 14.0, Tibco Software Inc, USA) and the SPSS statistics software, version 20.0 (SPSS Inc., Chicago, IL, USA). The normality of data distribution was evaluated using Kolmogorov-Smirnov test (Paper I) and Shapiro-Wilks test (Paper II). All the data is presented as means and standard deviation of mean (± SD), and percentage differences between "before "and "after" the cycling test. One-way analysis of variance (ANOVA) followed by Bonferroni post hoc was used to evaluate differences between data obtained before and after cycling at constant intensity (Paper I, Paper III). In Paper II, ANOVA followed by Scheffe' post hoc comparisons was used to identify group differences. In Paper III, Cohen's d effect sizes to identify statistical differences were determined (Cohen, 1988). Effect size coefficients were interpreted according to Hopkins (2009) with values of 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. A paired samples t-test for paired groups was assessed for statistical significance (Paper III). For Paper II and III Pearson correlation coefficients were used to assess the relationship between isometric MVC force of KE muscles, body and legs BMC, BMD; the sEMG MPF of skeletal muscles, maximum pedal force and ischial tuberosity size; cyclist anthropometry and seat pressure distribution variables. For all the above-mentioned analyses, value $p<0.05$ was considered to be statistically significant.

5. RESULTS

5.1. The relationship between bone mineral parameters, body composition and isometric strength of knee extensor muscles in male road cyclists and controls (Paper II)

5.1.1. Differences in bone mineral parameters, body composition and isometric strength of knee extensor muscles in male road cyclists and untrained controls

Table 2 presents the results of MVC, the total body composition, regional bone-free lean tissue, BMD and BMC in male road cyclists and untrained controls.

Table 2. The mean (± SD) differences between MVC, MVC force/body mass, body composition, regional bone-free lean tissue, BMD and BMC parameters between male road cyclists and untrained controls.

Variable	Cyclists (n=12)	Controls (n=12)
MVC force (N)	635.3 ± 103.7	656.6 ± 132.2
MVC force/body mass ($N \times kg^{-1}$)	8.6 ± 1.4	8.1 ± 1.5
Body fat %	13.7 ± 1.8	21.4 ± 4.3[b]
Right leg fat %	13.4 ± 3.3	21.0 ± 3.7[b]
Left leg fat %	13.2 ± 2.9	20.9 ± 4.0[b]
Body fat mass (kg)	10.1 ± 1.7	14.6 ± 3.0[a]
Right leg fat mass (kg)	1.7 ± 0.5	2.9 ± 0.7[b]
Left leg fat mass (kg)	1.7 ± 0.4	2.9 ± 0.8[b]
Total lean mass (kg)	60.2 ± 4.5	60.1 ± 5.2
Right leg lean mass (kg)	10.5 ± 0.9	10.2 ± 1.0
Left leg lean mass (kg)	10.4 ± 0.8	10.1 ± 0.9
Body BMC (kg)	2.9 ± 0.4	2.9 ± 0.1
Right leg BMC (kg)	0.6 ± 0.1	0.6 ± 0.1
Left leg BMC (kg)	0.6 ± 0.1	0.6 ± 0.1
Body BMD (g/cm^2)	1.20 ± 0.10	1.24 ± 0.08
Right leg BMD (g/cm^2)	1.36 ± 0.10	1.42 ± 0.13
Left leg BMD (g/cm^2)	1.38 ± 0.13	1.41 ± 0.12

Note: BMC: bone mineral content; BMD: bone mineral density; MVC: maximal voluntary contraction; [a] significant difference between cyclists and controls on a level of $p<0.05$; [b] $p<0.01$.

There were no significant differences ($p>0.05$) between the groups for the isometric MVC force relative to body mass characteristics. The cyclists had a significantly lower ($p<0.001$) body fat percentage, fat mass ($p<0.01$), and leg fat percentage ($p<0.001$) than the controls. No differences were found in whole body and leg BMC and BMD, lean body mass and leg lean mass between the cyclists and controls.

5.1.2. Relationship between isometric strength of knee extensor muscles, bone mineral parameters and body composition in male road cyclists and untrained controls

In only the group of controls, significant correlations were observed between MVC and bone mineral parameters, and body composition characteristics (Table 3).

Table 3. Correlation coefficients between isometric maximal voluntary strength of knee extensor muscles, bone mineral parameters and body composition in male road cyclists and untrained controls.

Variable	**MVC force (N)**	
	Cyclists (n=12)	**Controls (n=12)**
Total BMC (g)	0.19	0.69[b]
Right leg BMC (g)	0.10	0.66[a]
Left leg BMC (g)	0.19	0.69[b]
Total BMD (g/cm^2)	0.21	0.35
Right leg BMD (g/cm^2)	0.27	0.59[a]
Left leg BMD (g/cm^2)	0.37	0.69[b]
Lean body mass (kg)	0.28	0.66[a]
Right leg lean mass (kg)	0.22	0.52
Left leg lean mass (kg)	0.24	0.61[a]

Note: BMC: bone mineral content; BMD: bone mineral density; MVC: maximal voluntary contraction; [a] significant difference on a level of $p<0.05$; [b] $p<0.01$.

Strong positive correlations were found in male road cyclists between body mass and BMC ($p<0.01$), but there were no significant correlations in the comparison group of the controls (Table 4). The results revealed that BMC correlated positively with lean mass ($p<0.001$) but not with fat mass ($p>0.05$).

Table 4. Correlation coefficients between bone mineral parameters and body composition in male road cyclists and untrained controls (Paper II).

	Cyclists (n=12)						Controls (n=12)					
Variable	**BMC**	**BMD**	**Rleg BMC**	**Lleg BMC**	**Rleg BMD**	**Lleg BMD**	**BMC**	**BMD**	**Rleg BMC**	**Lleg BMC**	**Rleg BMD**	**Lleg BMD**
Body mass (kg)	**0.73^b**	0.46	**0.82^c**	**0.78^b**	0.50	0.47	0.38	-0.08	0.39	0.42	0.31	0.35
BMI (kg/m^2)	**0.65^b**	**0.69^b**	0.54	**0.59^a**	**0.86^c**	**0.76^b**	0.28	-0.07	0.27	0.29	0.24	0.27
Total fat mass (kg)	0.20	-0.03	0.40	0.29	0.06	0.08	-0.31	-0.41	-0.20	-0.11	-0.2	-0.13
Lean body mass (kg)	**0.85^c**	**0.60^a**	**0.89^c**	**0.87^c**	**0.58^a**	**0.57^a**	0.54	0.11	0.56	**0.60^a**	0.43	0.50
Right leg lean mass (kg)	**0.81^c**	**0.65^a**	**0.89^c**	**0.90^c**	0.52	**0.59^a**	**0.60^a**	0.28	**0.63^a**	**0.67^a**	**0.59^a**	**0.61^a**
Left leg lean mass (kg)	**0.81^c**	**0.60^a**	**0.89^c**	**0.89^c**	0.46	0.52	0.53	0.33	**0.59^a**	**0.64^a**	**0.58^a**	**0.63^a**

Note: BMC (kg): bone mineral content; BMD (g/cm^2): bone mineral density; BMI: body mass index; rleg: right leg; lleg: left leg; ^{a} significant difference between cyclists and controls on a level of $p<0.05$; ^{b} $p<0.01$; ^{c} $p<0.001$.

5.2. Changes in isometric strength and twitch contractile properties of knee extensor muscles after 30-min of cycling exercise at constant intensity in male road cyclists (Paper I)

5.2.1. Pre-exercise values of isometric strength and electrically evoked twitch characteristics of knee extensor muscles

Table 5 presents the results of pre-exercise values of electrically evoked twitch characteristics and isometric maximal voluntary strength of the KE muscles in male road cyclists.

Table 5. The mean (± SD) pre-exercise values of isometric maximal voluntary strength and electrically evoked twitch characteristics of the knee extensor muscles in male road cyclists (Paper I).

Variable	Cyclists n=10
	Pre-exercise
MVC force (N)	647.7 ± 87.5
PF (N)	70.4 ± 8.3
PAP (%)	128.8 ± 9.3
RFD (N/s)	631.8 ± 154.1
RR (N/s)	306.2 ± 96.8
CT (s)	0.095 ± 0.012
HRT (s)	0.093 ± 0.014

Note: PF: twitch peak force; PAP: post-activation potentiation; RFD: twitch maximal rate of force development; RR: twitch maximal rate of force relaxation; CT: twitch contraction time; HRT: twitch half-relaxation time; MVC: maximal voluntary contraction.

5.2.2. Changes in isometric strength and twitch contractile properties of knee extensor muscles after 30-min of cycling exercise at constant intensity

The values of twitch characteristics and isometric MVC force of the KE muscles in male cyclists are shown in Table 5. Following a 30-min cycling at constant intensity, the isometric MVC force of cyclists' KE muscles decreased significantly ($p=0.001$) compared to its pre-exercise level (Figure 7). There was no recovery of this parameter within 30 min following the end of the exercise ($p=0.037$), indicating non-recovery of isometric MVC force.

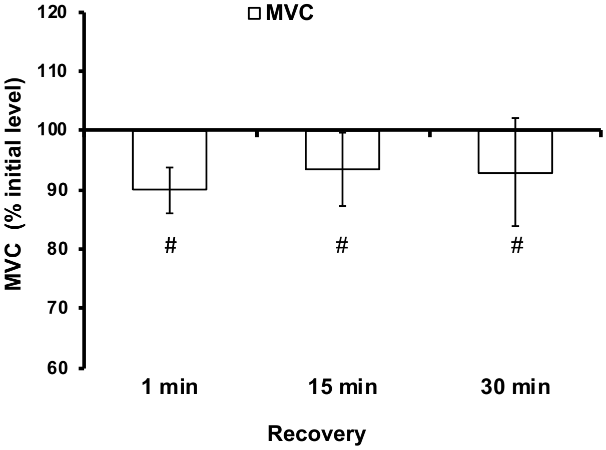

Figure 7. Changes in maximal voluntary contraction (MVC) force after 30-min cycling at constant intensity in male road cyclists (mean ± SD). # $p<0.05$ from pre-exercise value.

Figure 8 shows that the capacity for PAP of twitch contraction force decreased significantly ($p=0.01$) after a 5 s conditioning MVC, and PAP recovered within 15 min post-exercise.

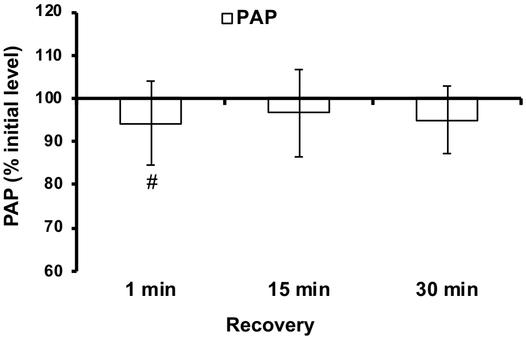

Figure 8. Changes in post-activation potentiation (PAP) after 30-min cycling at constant intensity in male road cyclists (mean ± SD). # $p<0.05$ from pre-exercise value.

After cycling at constant intensity, twitch RFD and RR decreased ($p=0.002$ and $p=0.003$; respectively), and these parameters recovered within 30 min post-exercise (Figure 9). There were no significant changes in twitch PF after the cycling exercise compared to the initial level (Figure 9).

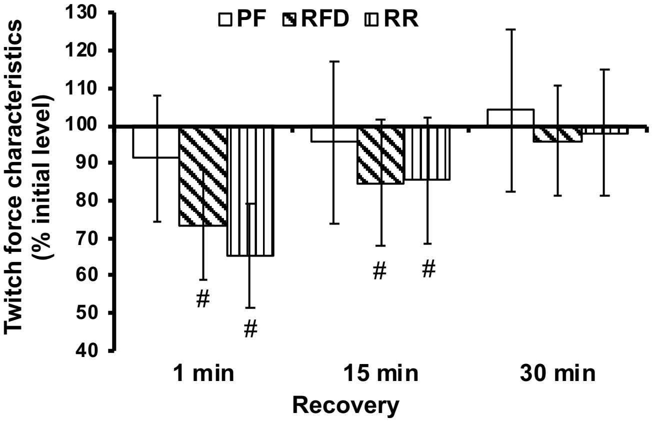

Figure 9. Changes in twitch peak force (PF), maximal rate of force development (RFD) and maximal rate of relaxation (RR) after 30 min cycling at constant intensity in male road cyclists (mean ± SD). # $p<0.05$ from pre-exercise value.

Twitch HRT was significantly prolonged after cycling exercise and recovered within 15 min after exercise (Figure 10). There were no significant changes in twitch CT (Figure 10) after the cycling exercise compared to the initial level.

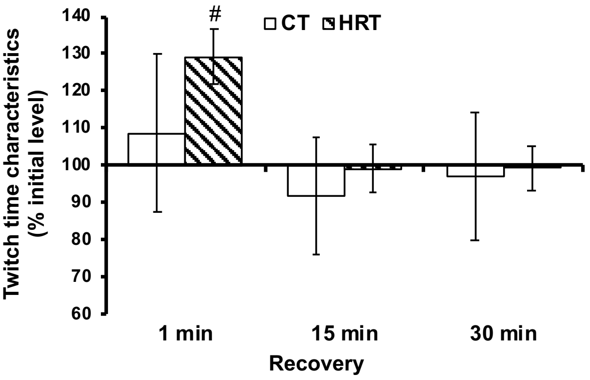

Figure 10. Changes in twitch contraction time (CT) and half-relaxation time (HRT) after 30-min cycling at constant intensity in male road cyclists (mean ± SD). # $p<0.05$ from pre-exercise value.

5.3. Seat pressure asymmetries and relationship with anthropometric characteristics and fatigue after 30 min of cycling exercise at constant intensity under laboratory conditions in male road cyclists (Paper III)

5.3.1. Pelvic anthropometric characteristics and changes in seat pressure after 30 min of cycling exercise at constant intensity under laboratory conditions in male road cyclists

DXA measurements of pelvic anthropometry in road cyclists are reported in Table 6.

Table 6. The mean (± SD) values of pelvic anthropometry, measured by DXA, in male road cyclists (n=12).

Variable	Mean ± SD
Height of pelvis (cm)	24.3 ± 1.5
Width of pelvis width (cm)	26.4 ± 2.7
Right ischial tuberosity size (cm)	4.1 ± 0.3
Left ischial tuberosity size (cm)	4.2 ± 0.4

Note: DXA: Dual energy X-ray absorptiometry.

The mean pressure indicators of the gluteal area changed significantly after the exercise (left, p=0.02; right, p=0.01) (illustrated in Figure 11), and a significant decrease in peak pressure around the left ischial tuberosity (p=0.01) occurred (Figure 12). According to the mean pressure indicators, the differences between the right and the left sides of the gluteal area were nonsignificant (before exercise, p=0.44; after exercise, p=0.11) (Figure 11). The observed peak pressures of effect sizes were 0.06 for the right ischial tuberosity and 0.6 for the left ischial tuberosity. After the exercise, the ischial tuberosity peak pressure ratio of right to left was significant (p=0.005; Cohen's d=0.96) (Figure 13). There were no significant differences in the sitting relative contact area (p>0.05) (Figure 14) and sitting stability evaluated by the length of COP trajectory (p>0.05) after a 30-min cycling exercise at 50% W_{peak} at a constant intensity.

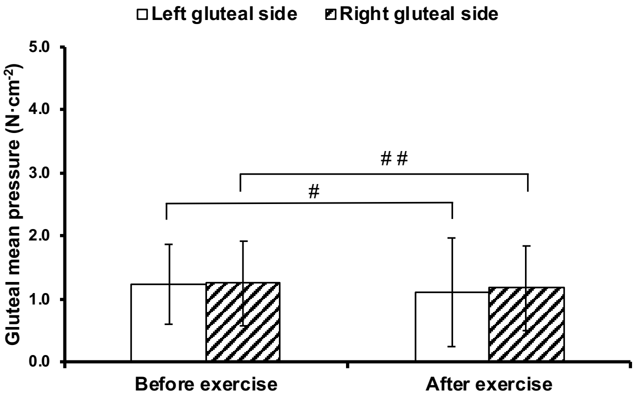

Figure 11. Mean (± SD) pressure under the gluteal area before and after 30-min constant cycling exercise at a constant intensity in male road cyclists (n=12). # p<0.05; # # p<0.01.

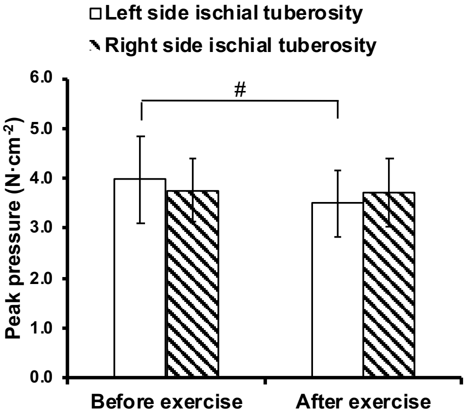

Figure 12. Mean (± SD) peak pressure under the left and right ischial tuberosity before and after 30-min cycling exercise at constant intensity in male road cyclists (n=12). # p<0.05.

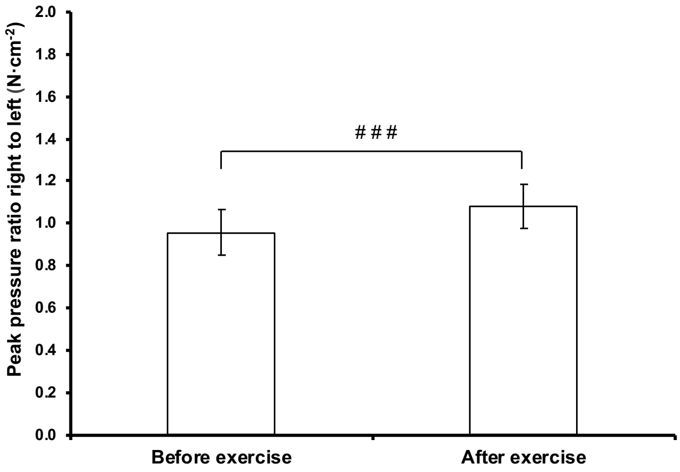

Figure 13. Mean (± SD) peak pressure right-to-left ratio before and after 30-min cycling exercise at constant intensity in male road cyclists (n=12). # # # $p<0.001$.

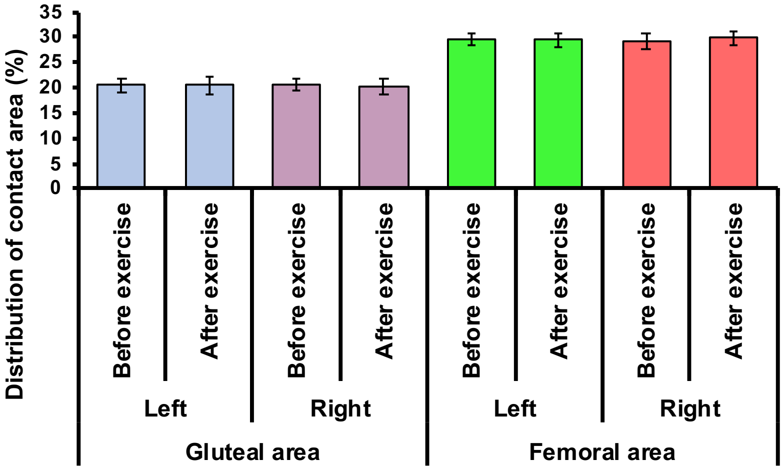

Figure 14. Mean (± SD) contact area distribution of the left and right gluteal area, and left and right femoral area. There were no significant differences in the distribution of contact area before and after the exercise.

5.3.2. Cycling load and changes in surface electromyogram power frequency parameters during 30-min cycling exercise at constant intensity in male road cyclists

Table 7 presents the mean variables examined during the 30-min constant load cycling in male road cyclists (Paper III).

Table 7. The mean (± SD) variables during 30-min cycling exercise at constant intensity in male road cyclists.

Variable	Cyclists n=12
Maximal pedal force (N)	361.5 ± 174.7
Pedal force (N)	133.4 ± 15.4
Cadence per minute	85.3 ± 5.0
Heart rate per minute	140.1 ± 6.8

Changes in surface electromyography characteristics during cycling at constant intensity are presented in Table 8. Significant MPF changes occurred only in the back muscles.

Table 8. The mean (± SD) variables in surface electromyogram spectral mean power frequency (MPF) in male road cyclists during a 30-min cycling exercise at constant intensity at 50% of W_{peak} in the first and last minute.

MPF (Hz) Variable	First min	Last min	% change	p-value	Effect size (Cohen's d)
Right m. gluteus medius	76.5 ± 14.2	77.3 ± 14.8	1.1	0.72	0.05
Left m. gluteus medius	85.7 ± 24.2	82.7 ± 23.2	-3.5	**0.03**[a]	0.12
Right erector spinae L3	58.5 ± 14.0	50.1 ± 15.1	-14.3	**0.01**[a]	**0.55**
Left erector spinae L3	55.4 ± 16.3	56.8 ± 20.8	2.6	0.84	0.07
Right m. biceps femoris	61.5 ± 14.9	66.1 ± 20.0	7.4	0.47	0.25
Left m. biceps femoris	74.4 ± 22.8	69.0 ± 21.4	-7.2	0.43	0.23
Right m. vastus lateralis	98.3 ± 14.6	98.8 ± 17.6	0.6	0.84	0.03
Left m. vastus lateralis	96.8 ± 20.4	96.2 ± 26.7	-0.7	0.87	0.02
Right m. rectus femoris	79.3 ± 9.9	81.2 ± 10.3	2.4	0.35	0.18
Left m. rectus femoris	84.4 ± 17.6	79.1 ± 19.2	-6.3	0.37	0.27

Note: W_{peak}: peak power output; [a] significant difference after cycling exercise compared to the initial level.

5.3.3. Correlations between surface electromyographic power spectral parameters of the skeletal muscles, maximum pedal force, and pelvic anthropometry parameters in male road cyclists

Correlations between sEMG MPF, maximum pedal force, and pelvic anthropometry are shown in Table 9. Significant correlation coefficients were found between maximum pedal force and sEMG MPF, and also between maximum pedal force and ischial tuberosity size (Figure 15). No significant correlations were found between average pedal force production, sEMG MPF, and pelvic anthropometry parameters (p>0.05).

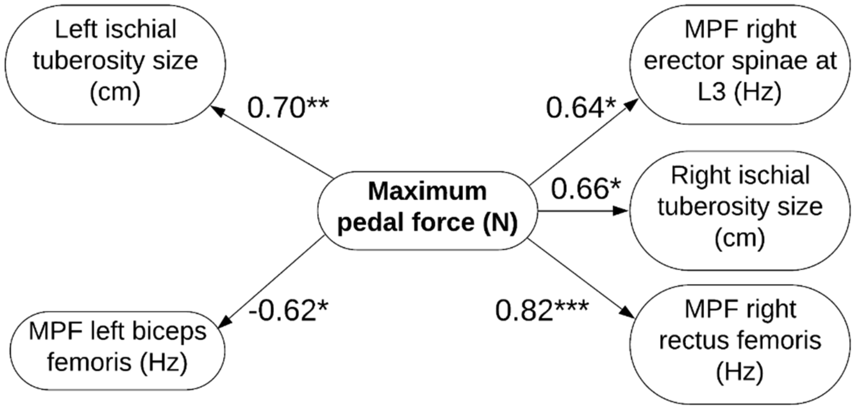

Figure 15. Significant correlations with maximum pedal force during the cycling exercise, skeletal muscle fatigue, and ischial tuberosity size. * p<0.05; ** p<0.01; *** p<0.001.

Table 9. Pearson correlation coefficients between seat pressure distribution variables, anthropometric characteristics, and surface electromyographic mean power spectral frequency (MPF) of skeletal muscles of participants.

	Before left fem. (N/cm^2)	Before right fem. (N/cm^2)	Before left glut. (N/cm^2)	Before right glut. (N/cm^2)	After left fem. (N/cm^2)	After right fem. (N/cm^2)	After left glut. (N/cm^2)	After right glut. (N/cm^2)	Before left ischial tuberosity (N/cm^2)	After left ischial tuberosity (N/cm^2)	Before right ischial tuberosity (N/cm^2)	After right ischial tuberosity (N/cm^2)
Body mass (kg)	0.52	0.33	**0.69**^{a}	0.34	**0.79**^{b}	0.43	0.41	0.37	0.07	-0.23	0.01	-0.07
Height (cm)	0.09	-0.42	0.06	-0.13	0.39	0.06	0.54	0.02	**0.60**^{a}	0.45	**0.60**^{a}	0.48
Pelvis width (cm)	-0.14	-0.47	0.09	0.17	0.02	-0.11	0.55	0.38	**0.72**^{b}	0.29	**0.91**^{c}	**0.65**^{a}
Right ischial tuberosity size (cm)	0.30	-0.13	-0.18	-0.35	-0.14	-0.12	-0.05	0.04	0.30	0.12	0.30	0.34
Left ischial tuberosity size (cm)	0.33	-0.15	-0.05	-0.24	-0.05	-0.03	0.17	0.15	0.50	0.32	0.47	0.53
MPF biceps right (Hz)	-0.33	0.19	0.38	**0.61**^{a}	0.10	0.20	0.42	**0.68**^{a}	0.29	0.14	0.57	0.32
MPF biceps left (Hz)	**-0.60**^{a}	-0.03	0.06	0.23	-0.21	-0.26	-0.39	0.13	-0.29	-0.45	0.06	-0.45
MPF rectus femoris right (Hz)	0.42	0.30	-0.10	-0.26	0.12	0.39	0.07	-0.12	-0.03	0.35	-0.22	0.24
MPF rectus femoris left (Hz)	-0.05	-0.30	-0.18	-0.35	0.19	-0.08	0.20	-0.18	0.32	0.20	0.34	0.20
MPF erector spinae L3 right (Hz)	-0.18	-0.27	-0.42	**-0.61**^{a}	-0.27	-0.17	-0.16	-0.51	0.12	0.37	0.06	0.14
MPF erector spinae L3 left (Hz)	0.06	-0.10	-0.24	-0.20	-0.56	-0.48	-0.10	-0.10	0.14	0.19	-0.13	0.01

Note: Fem – femoral area; glut – gluteal area; ^{a} significant difference on a level of $p<0.05$; ^{b} $p<0.01$; ^{c} $p<0.001$.

6. DISCUSSION

6.1. The relationship between bone mineral parameters, body composition, and the isometric maximal voluntary strength of knee extensor muscles in road cyclists and untrained controls

This study aimed to evaluate the relationships between bone and body composition parameters and isometric MVC force of KE muscles in highly trained male road cyclists and untrained controls. As a result, the study intended to provide a more comprehensive understanding of long-term adaptation to cycling and its relationship with bone and body composition characteristics.

The present study revealed that long-term adaptation to cycling has strong relations between bone mineral parameters and body mass, as well as body and leg lean mass, but not with KE muscle isometric strength.

Road cyclists have lower levels of body fat and leg fat than controls, which allows them to maintain optimal body mass. Performance in cycling is positively correlated with a lower body mass (Martínez-Noguera et al., 2023). All the cyclists in this study had low body and leg fat parameters that have also been reported by several authors (Baker & Reiser, 2017; Hilkens et al., 2023; Mojock et al., 2016). Studies comparing body fat and fat-free mass values between professional and amateur cyclists have reported that professional cyclists have a lower percentage (8–10%) of body fat and an average fat-free mass of 62.5 kg, in contrast to amateurs' body fat value of 11% and fat-free mass of 60 kg (Medelli et al., 2009; Penteado et al., 2010). Estonian high-level cyclists in this study had a higher average value of 13.6% in body fat with fat free mass of 60.2 kg. Fat mass has been shown to have an effect on bone mass (Medelli et al., 2009), but according to this study, low body fat percentage was not related to low bone mineral parameters.

The present study demonstrated that fat tissue must be distinguished from lean tissue, also BMI is not the only factor that determines muscle functional status, which involves skeletal muscle strength. The study did not show differences in muscle strength values between the road cyclists and untrained controls. However, the isometric MVC force of the KE muscle related to body mass was slightly higher in the road cyclists compared to the controls. As body size appears to affect maximal strength and power generation and also the adaptation caused by long-term endurance training (Jaric, 2002), it seemed unreasonable to expect very high isometric MVC force values in male road cyclists. The majority of endurance athletes, including road cyclists, use predominantly slow-twitch fibres with low-force generating capacity during trainings compared to untrained controls, who might be more able to recruit fast-twitch fibres to develop muscle strength (Izquierdo et al., 2004; Mitchell et al., 2018; Segerström et al., 2011).

Several studies have shown that elite male cyclists have low BMD compared to controls (Hilkens et al., 2023; Martínez-Noguera et al., 2023), which is not consistent with the results of the present study. It has been reported that professional cyclists have an average BMD of 1.145 g/cm^2 compared to 1.187 g/cm^2 in amateurs (Medelli et al., 2009). However, the North American Health Survey (NHANES III) data show that total BMD values above 1.033 g/cm^2 are normal (Looker et al., 1997), and all the participants in this study were above this value. Nonetheless, this study observed similar BMD values ($p>0.05$) in the cyclists compared to the controls, 1.20 ± 0.10 and 1.24 ± 0.08 g/cm^2, respectively. In addition, the cyclists had nonsignificantly lower BMD values in the lower extremities as well. Furthermore, Smathers et al. (2009) did not observe significant differences in the total body BMD between male cyclists and controls but found lower values among athletes. A possible explanation why Estonian top cyclists do not suffer from significantly low BMD is due to the climate conditions, which offer many weight-bearing activities during winter in addition to indoor cycling. Weight-bearing exercises are important at a young age in order to prevent bone problems later in life (González-Agüero et al., 2017). It is likely that cyclists in Estonia have done more weight-bearing exercises than their southern counterparts in the early stages of their careers.

Another significant bone health marker is BMC. In the present study, similar body BMC values (2.9kg) were found in cyclists and a group of controls. Martinez et al. (2023) and Medelli et al. (2009) reported comparable BMC values in professional cyclists similar to this study. Likewise, the above-mentioned authors and this study found a correlation between BMC and body mass in male road cyclists ($r=0.73$; $p<0.01$). These parameters did not appear to be related in the controls based on the results of the present study, showing the importance of regular training history for bone growth and development.

The road cyclists had similar lean mass compared to the controls. It is in agreement with the study by Pimentel et al. (2019) that compared BMD and lean mass parameters between cyclists and non-cyclists. It has been suggested that body mass and lean mass have an important relationship with BMC in road cyclists (Martínez-Noguera et al., 2023; Medelli et al., 2009). The results of this study highlighted that BMC and BMD are more closely related to total lean body mass due to the stronger correlations observed in the cyclists. An increase in lean mass generates increased mechanical loading on bones and therefore it has been shown to positively affect bone health not only in cyclists but also in controls, as was seen in this study. Contrary to Martínez-Noguera (2023) and Medelli (2009), the present study did not find a relationship between fat mass and BMC in any group. Nonetheless, fat mass was significantly higher in the control group than in male road cyclists. The study indicates that lean mass is more closely related to BMC and BMD than fat mass. These findings highlight the significance of regular training to bone adaptations relations with an increased lean mass effect on bone mineral parameters.

The results of the correlation analysis from Paper II showed strong correlation of isometric MVC force with bone and body composition parameters only in groups of the untrained controls. However, there were no significant differences in the isometric MVC force of KE muscles variables between cyclists and controls. The results of the present study indicate that long-term adaptation to cycling has no effect on the relationship between muscle functional capacity and bone mineral parameters and body composition. A possible explanation for this could be several neural factors that affect maximal strength (recruitment, coordination and firing frequency of motor units) as well as changes in muscle quality as a result of endurance training.

6.2. Changes in knee extensor muscles contractile characteristics after cycling at constant intensity in road cyclists

In the present study, cycling exercise at a constant intensity induced a decrease in voluntary and electrically elicited force-generation capacity of the KE muscles. A marked peripheral fatigue was observed by a decrease in electrically evoked twitch force generation and relaxation. Furthermore, the results of this study showed that electrically evoked twitch force characteristics recovered faster after cycling exercise at constant intensity compared to the voluntary force capacity of the KE muscle.

Male road cyclists reported a 10% decrease in isometric MVC force capacity after cycling exercise at constant intensity compared to the initial level. An indicator of muscle fatigue is a reduction in the force a muscle can exert or the inability to sustain further exercise at a required level of power (Enoka & Stuart, 1992). The reduction in isometric MVC force after exercise is typically associated with peripheral electrical and mechanical failures. However, the findings of this study demonstrate also the importance of central contraction mechanisms. Comparing the same characteristics with the previous studies, there was a similarity with Lepers et al. (2000) and Bentley et al. (2000), showing about a 9–13% decrease in isometric MVC force immediately after cycling exercise. A decrease in isometric MVC force after exercise might be caused by processes associated with the central command of contraction (Sesboüé & Guincestre, 2006), as well as peripheral processes associated with intramuscular electrical and mechanical failures (Gandevia, 2001). Peripheral fatigue is caused by contractile failure in active muscles, indicating changes in muscle action potential transmission mechanisms and defined as a decrease in evoked force, whereas central fatigue is characterized by a decrease in recruitment of new motor units and/or a reduction in firing the frequency of active motor units, defined as a decrease in maximal voluntary muscle activation (Gandevia, 2001).

The results of this study indicated that time-course characteristic CT and the resting twitch PF did not differ significantly after exercise compared to the measurements taken before exercise. It is possible that cyclists with a long training history had no decrease in PF due to the lower levels of type II muscle fibres and also a smaller muscle cross-sectional area (Häkkinen & Keskinen, 1989). It has previously been reported that endurance-trained athletes have a smaller twitch PF than power-trained athletes and sedentary individuals (Pääsuke et al., 1999). As twitch PF in the cyclists was not decreased after constant intensity cycling exercise in the present study, it could be concluded that the decrease in voluntary strength is not only related to the decrease in muscle fibre contraction properties but rather to the decrease in the ability to mobilize motor units.

An indicator that shows the enhancement of twitch force following a conditioning MVC is called PAP (Boullosa et al., 2018). It has been accepted that this mechanism of PAP is associated with the enchancement of the interaction between myosin-actin and excitation-contraction coupling (Grange et al., 1993). Studies have suggested that PAP is caused by phosphorylation of myosin regulatory light chains, which are Ca^{2+} dependent (Persechini et al., 1993). A review study by Boullosa et al. (2018) on endurance athletes suggested the existence of PAP mechanisms during and after endurance performances. PAP presents the percentage increase in twitch PF over resting twitch PF. In the present study, the PAP of twitch contraction force in the KE muscles significantly reduced (6%) and it recovered within 15 min post-exercise. It appears that a reduction in PAP after constant load cycling exercise is indicative of the failure to phosphorylation the regulatory light chains of myosin (Persechini et al., 1993), which could lead to a decrease in muscle power and force production following this exercise. The monitoring of PAP, muscle fatigue, and perceptual fatigue during training sessions could be very beneficial for understanding how cyclist and other endurance athletes adapt acutely and chronically to different types of training, including constant load cycling exercise.

The present study represents marked peripheral fatigue found by the changes of electrically evoked twitch RFD, RR, and the prolongation of HRT. A reduction in the twitch RFD (27%) and RR (33%) occurred in the cyclists immediately after the end of constant cycling exercise at constant intensity compared to the pre-exercise level, whereas these parameters were significantly lower after a 15-min recovery period and recovered in 30 min after cycling exercise. Twitch RFD is primarily determined by cross-bridges development between myosin and actin in active muscle fibres, while RR is highly dependent on Ca^{2+} pumping mechanism (Westerblad et al., 1997). The results of this study suggest that the efficiency of these intramuscular processes in KE muscles is significantly reduced in cyclists after 30 min cycling exercise at constant intensity.

After 30 min of cycling exercise at a constant intensity, cyclists' HRT was significantly (29%) prolonged, and it recovered within 15 min after the exercise to the initial pre-exercise level. Previous research has also noted the decrease of muscle relaxation during fatigue (Lepers et al., 2000). HRT is influenced by the rate at which the sarcoplasmic reticulum can sequester Ca^{2+}, and Ca^{2+} release is markedly depressed with fatigue in athletes' muscles (Li et al., 2002).

6.3. Seat pressure changes after cycling exercise at constant intensity in association with pelvic anthropometric parameters and neuromuscular fatigue in road cyclists

This experimental study evaluated seat pressure asymmetries before and after a 30-min cycling at constant intensity in association with pelvic anthropometric parameters and skeletal muscle fatigue. According to the main findings of this dissertation, a significant asymmetry in seat pressure under ischial tuberosity was found based on the peak pressure right-to-left ratio after constant load cycling exercise.

Moreover, the relationship between pelvis width and pressure under the ischial tuberosity occurred bilaterally before exercise, but this relationship was only revealed on the dominant side after exercise. In addition, the decrease in muscle activation frequency was observed only on the dominant side erector spinae.

The study provides a novel approach to measure the size of ischial tuberosities by DXA and to study relationships with these parameters after exercise. There are no studies that have evaluated seat pressure after cycling exercise at constant intensity. More commonly, the distance between the ischial tuberosity (the pelvis' points of contact) has been evaluated in studies mostly conducted in the saddle (Bressel et al., 2007, 2010; Verma et al., 2016). In practice, researchers measure the width of ischial tuberosities by sitting on a foam block (Chen, 2018; Potter et al., 2008). However, the size of ischial tuberosities could be accurately determined via DXA, and valuable data could be obtained after certain cycling exercises, not only in the saddle during the exercise.

In the present study, a significant change in mean seat pressure of left-to-left and on right-to-right gluteal areas was demonstrated after 30 min cycling at constant intensity. Significantly lower values of mean pressure were found after cycling exercise compared with the baseline data (left p=0.02; right p=0.01). However, there was no significant difference in the gluteal area between the right and left body sides before (p=0.44) or after exercise (p=0.11). Therefore, it can be concluded that cyclists with long-term adaptation to cycling modify and improve their positions on the bicycle in a way that is imperceptible, it is solely determined by the presented seat pressure variables.

In addition, highly adapted cyclists have developed perceptions, enabling them to select comfortable saddles based on their comfort level. This study indicated that 30 min of cycling at 50% W_{peak} resulted in a decrease in sEMG MPF, despite no change of gluteal mean pressure between body sides. Carpes et al. (2009) reported low back pain as a negative factor for normal pelvis movement. Although the cyclists in this study did not have any back problems, it is likely that low back muscle fatigue, measured by sEMG power spectrum, affected seat pressure after cycling exercise.

Bressel and Larson (2003) demonstrated differences between the predictors of mean seat pressure and peak pressure. Present study showed a significant (p=0.01) decrease in peak pressure under the left ischial tuberosity after the 30-min cycling exercise at constant intensity. Furthermore, a postural shift was observed with significant (p=0.005) asymmetry in the ischial tuberosity peak pressure ratio from right to left after exercise. Consequently, there may be a significant decrease in blood flow under the ischial tuberosity. All these changes could adversely affect cyclists' posture after exercise, potentially leading to overuse injuries. By addressing and reducing asymmetry, cyclists can lower the risk of injuries and improve overall performance.

The results of the present study showed a positive correlation between cyclists' body mass and left gluteal pressure before the exercise. Interestingly, it was not seen after the exercise as the correlation revealed only on the left femoral area, confirmed by a decrease in pressure parameters on the gluteal area. The results of this study contrast with the study by Bressel et al. (2010) who found that cyclists with a lower body mass displayed significantly greater peak pressure values than heavier cyclists because of less subcutaneous tissue covering the ischiopubic bone. Instead, the taller the cyclist was, the stronger the relation between the non-dominant side of pressure under the ischial tuberosity before and after the cycling exercise at constant intensity. The most likely explanation for this is that seat pressure was measured after the cycling exercise, not in the saddle during the exercise, where taller cyclists' pelvic angle is different as they lean forward.

It has been suggested that the width of the saddle affects the pressure distribution, and these distributions may be dependent on the pelvis size and the area that is in contact with the saddle (Chen, 2018; Potter et al., 2008). In previous studies, it has been shown that the saddle should be widened to better support the ischium since a larger pressure area result in a larger dispersion of pressures (Chen, 2018; Lin et al., 2023). According to Lin et al. (2023) study with female cyclists, a saddle that was 1 cm wider than cyclist's ischial tuberosities improved pressure distribution and increased comfort. Chen et al. (2018) showed that the width of the male cyclist's ischial tuberosity is smaller than that in women. Since the width of the pelvis and the distance between the ischial tuberosities are proportional, both wider measurements can reduce the load on the ischial tuberosities (Chen, 2018; Lin et al., 2023; Vicari et al., 2023). The results of the present study indicated that pressure only under the dominant side of the ischial tuberosity was associated with pelvis width after a 30-min cycling exercise at constant intensity, although a strong correlation between pelvis width and pressure under the ischial tuberosity occurred bilaterally before the cycling exercise. Moreover, a correlation was not found between the pressure under the ischial tuberosities and the size of the ischial tuberosities and the height of the pelvis. There is a possibility that the significant decrease in sEMG power spectrum MPF of the dominant-side erector spinae after exercise is due to changes in pressure parameters, or vice versa.

A connection has been found between the mean pressure of the saddle with an increase in pedal force (Holliday et al., 2019). The correlation results of the present study were found between the maximum pedal force and the size of ischial tuberosities. It has been shown that pedal force and muscle activation changes in force may be subconscious strategies for maintaining power (Dingwell et al., 2008). Based on this study, when assessing the relationships with pedal force, the size of the ischial tuberosity and the width of the pelvis should also be considered.

Several parameters are used to evaluate fatigue in sEMG studies, for example, an increase in sEMG signal amplitude or a decrease in mean/median power frequency (Holliday & Swart, 2022; Lindstrijøm et al., 1977; Srinivasan & Balasubramanian, 2009). In previous studies, the sEMG power spectrum MPF was found to be an accurate indicator of muscle fatigue, which is why it has been widely used in assessing muscle fatigue (Balasubramanian & Jayaraman, 2009). It has been reported that MPF decreases in isometric and in dynamic fatiguing contraction conditions (Dingwell et al., 2008; Wang et al., 2018). Similarly, the present study observed a decreased pattern in the sEMG signal. In the present study, sEMG analysis during cycling revealed a significant decrease after the exercise in MPF in right erector spinae muscle at L3. However, there was no significant decrease in MPF in the thigh muscles. Both central and peripheral factors are involved, but the peripheral has been proposed mainly to cause MPF shift decrease (Balasubramanian & Jayaraman, 2009). sEMG power frequency MPF decreased significantly after 30 min of constant intensity cycling exercise in this study, indicating significant fatigue of the right erector spinae muscle. MPF decreases may be attributed to decreased muscle fibre conduction velocity and synchronized motor unit firing (Bigland-Ritchie et al., 1986). Gibson and colleagues (2001) found that fatigue occurs when the skeletal muscles become less capable of generating force during prolonged bicycling as a result of metabolic changes. Bernando et al. (2012) have presented with their study that overuse injuries due to fatigue were 51.5% of all registered injuries and 67.9% of them affected the lower limbs. The findings of this study are consistent with the previous research conducted by Clarsen et al. (2010), where the low back was 30% of the most common anatomical location for overuse injuries in the group of cyclists. On the other hand, Clarsen et al. (2010) pointed out that the most prevalent overuse injury is knee pain. However, this study did not reveal significant changes in thigh muscle patterns after cycling exercise due to long-term adaptation to cycling.

In the present study, a positive association was found between maximum pedal force and a decrease in dominant-side back muscle and rectus femoris MPF frequency. Maximum pedal force was negatively correlated with the left biceps femoris MPF. The results suggest that competitive male road cyclists experience compensatory mechanisms towards their dominant side when they perform cycling exercises at a constant intensity. As a result of high adaptation to cycling, cyclists' muscle patterns have been mainly altered in the back muscles rather than thigh muscles. Consequently, if the maximum pedal force increases during cycling at constant intensity, it indicates that the muscle pattern has changed. The more these changes are minimized between the left and right body sides, the lower the chances of musculoskeletal disorders occurring, including those associated with sitting.

6.4. Limitations and strengths of the dissertation

There are some limitations to consider in connection with the present study. Primarily, the relatively small sample size and variety of qualification (aged 18–32) of male road cyclists, due to difficult recruitment compared to the availability of lower-level athletes. However, in accordance with the present study, there are studies with a similar sample size (Decorte et al., 2012), and the group of participants in this study was homogeneous concerning their training history and level of performance. Chapman et al. (2006) proved the importance of that because there is evidence that neuromuscular adaptations vary with the training status. Secondly, the participants were healthy competitive male road cyclists, so it is unclear whether the findings can be generalized to the individuals with compromised loading, such as those who have recently suffered from musculoskeletal disorders, surgeries, or injuries affecting the sitting position. Furthermore, this study only included male participants, so future studies could include female participants. As the testing was done after the preparation season in spring, it would be interesting to see if contractile characteristics differ at the end of the season and if seat asymmetries are more apparent. Additionally, this study only examined seat pressure changes. As a result, it was impossible to determine whether bilateral postural imbalances also affected sitting patterns.

This controlled study also has several strengths that contribute to its significance. Firstly, it includes Estonian top high-level male road cyclists classified as tier 3 – highly trained/national level in terms of the classification framework (McKay et al., 2022). To our best knowledge, there are no published studies investigating the effects of before and after cycling exercise at constant intensity on the relationship between pelvic anthropometric parameters, sEMG power frequency parameters, and seat pressure variables. This study had a novel approach to measure the size of the ischial tuberosities by DXA rather than evaluating the distance between the ischial tuberosity (the pelvis' points of contact) as mostly has been done in saddle (Bressel et al., 2007, 2010; Verma et al., 2016). The results of this study also provide practical knowledge about avoiding overuse injuries from seat pressure asymmetries. Variable intensities with body movements can prevent these asymmetries, regardless of how ergonomic the bicycle's saddle or seated position may be. It is important to understand that changes can occur under ischial tuberosities even if the cyclist appears balanced overall. For the purpose of determining whether asymmetry differences could be prevented after cycling exercise at constant intensity, cyclists should be tested with asymmetrical cycling pants, which have a higher pad under the dominant ischial tuberosity and a lower pad under the non-dominant ischial tuberosity.

7. CONCLUSIONS

1. In male road cyclists, strong associations between bone mineral parameters and body mass occurred compared to the controls, whereas muscle strength was not associated with bone mineral and body composition parameters in the cyclists.
2. In male road cyclists, a significant reduction in the voluntary force generation capacity of the knee extensor muscles with the development of peripheral muscle fatigue occurred after 30 minutes of constant-intensity cycling exercise.
3. Following a 30-minute recovery period after a 30-minute cycling exercise at constant intensity, the electrically evoked twitch force characteristics of the knee extensor muscles recovered faster than voluntary force generation capacity.
4. Neuromuscular fatigue, assessed by electromyographic spectral parameters in male road cyclists during a 30-minute submaximal cycling exercise at constant intensity, is more observed in the back muscles than thigh muscles.
5. In male road cyclists, a significant seat pressure asymmetry was observed by the peak pressure right-to-left ratio after a 30-minute submaximal cycling exercise at constant intensity under the ischial tuberosity.

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SUMMARY IN ESTONIAN

Seosed keha koostise ja lihasjõu näitajate vahel ning adaptiivsed muutused konstantse intensiivsusega jalgrattasõidul laboratoorsetes tingimustes meessoost maanteeratturitel

Jalgratturid kui vastupidavusala sportlaste esindajad otsivad pidevalt võimalusi, kuidas väsimuse tingimustes sooritusvõimet säilitada ning väsimuse süvenemist edasi lükata (Abbiss & Laursen, 2005). Oluline on sealjuures vältida vigastusi, mis tulenevad lisaks traumadele ka ülekoormusest, sealhulgas kehaasendi muutustest väsitaval koormusel (Albero et al., 2023; De Almeida Azevedo et al., 2022; Girard et al., 2013). On leitud, et jalgratturitel esineb traumaatiliste vigastustega võrdselt ka ülekoormusvigastusi. Kaheksakümne viiel protsendil jalgratturitest on leitud karjääri jooksul ühe või mitme ülekoormusvigastuse esinemine (Dettori et al., 2006).

Väsimuse tekkides muutub jalgratturitel automaatselt lihaste aktivatsioonimuster ning selle tulemusena muutub oluliselt pedaalimistehnika ning lihaste aktiivsus koormusel (Balasubramanian & Jayaraman, 2009; Hug & Dorel, 2009; Wang et al., 2018). Jalgrattasõidu ajal töötavad peamiselt alajäsemete- ja seljalihased ning nende lihaste väsimine koormuse ajal mõjutab koormusjärgset isteasendit (Bini & Hunter, 2021; Rooney et al., 2020; Visentini et al., 2022). Väga palju tähelepanu on viimastel aastatel pööratud luu- ja lihaskonna vaevuste ennetamiseks seoses pikaajaliste staatiliste asenditega kontoritoolil istudes. Märksa vähem teatakse sarnaste mustrite esinemisest kehalise koormuse järgselt, sh konstantse koormusega jalgrattasõidul. On teada, et sellist konstantset koormust kasutatakse laialdaselt rehabilitatsioonis, näiteks treeninguna veloergomeetril. Ülaltoodud koormus, eriti seoses väsimuse tekkega pikaajalisel kehalisel tööl, võib aga olla ülekoormusvigastuste üheks riskifaktoriks.

Käesoleval ajal on kirjanduses vähe informatsiooni skeletilihaste kontraktiilsete omaduste, sealjuures aktiivsusjärgse potenseerumise kohta pikaajalise konstantse jalgrattasõidu järgselt (Garzia, 2013; Kordi et al., 2021). Samuti on vähe andmeid luutiheduse, keha koostise ja lihasjõu vahelistest seostest pikaajalise treenigstaažiga maanteejalgratturitel.

Uurimistöö eesmärk ja ülesanded

Doktoritöö eesmärgiks oli analüüsida keha koostise, luutiheduse ja lihasjõu näitajaid ning adaptiivseid muutusi konstantse intensiivsusega jalgrattasõidul meessoost maanteejalgratturitel.

Uurimustöös püstitati järgmised ülesanded:

1. Selgitada välja seosed keha koostise ja luutiheduse ning reie nelipealihase isomeetrilise tahtelise jõu näitajate vahel meessoost maanteejalgratturitel ning mittetreenitutel.

2. Selgitada välja reie nelipealihase tahtelise isomeetrilise jõu ning elektrostimulatsiooniga esile kutsutud üksikkontraktsiooni näitajate muutused 30-min konstantse koormusega jalgrattasõidu mõjul laboratoorsetes tingimustes.
3. Selgitada välja survejõudude jaotuvuse asümmeetria isteasendis pärast 30-min konstantse intensiivsusega jalgrattasõitu laboratoorsetes tingimustes ning leida seosed vaagna antropomeetriliste näitajate ning lihasväsimuse näitajate vahel meessoost maanteejalgratturitel.

Uuritavad ja metoodika

Uuringus osales kokku 12 meessoost maanteejalgratturit vanuses 18–30 a. ja 12 kontrollrühma liiget vanuses 20–34 a. Kõik uuritud sportlased kuulusid Eesti absoluutsesse paremikku. Osalejatel määrati Tartu Ülikooli kinesioloogia ja biomehaanika laboris enne uuringuga alustamist antropomeetrilised näitajad ning enne, vahetult pärast ja 15 ning 30 min pärast koormust reie nelipealihase tahteline isomeetriline maksimaaljõud ning kontraktiilsed omadused spetsiaalse elektromehaanilise dünamomeetriga. Kõigil uuringus osalejatel määrati Tartu Ülikooli Chemicumis 1–2 nädalat enne uuringuga alustamist keha koostise ja luutiheduse näitajad densitomeetria meetodil (Lunar Corp., Madison, WI, USA). Kontrollrühm konstantse koormusega jalgrattasõitu ei sooritanud ja lihasjõu näitajad määrati neil ühekordselt.

Jalgratturitega viidi läbi kaks uuringut laboratoorsetes tingimustes. Esimeses uuringus sooritasid jalgratturid 30-min konstantse intensiivsusega (250 W) jalgrattasõidu Tacx Cosmos ergomeetril (Tacx B.V., Netherlands) isikliku jalgrattaga. Enne, vahetult pärast ja 15 ning 30 min pärast konstantse koormusega jalgrattasõitu määrati neil reie nelipealihase tahteline isomeetriline maksimaaljõud ning kontraktiilsed omadused dünamomeetriga.

Teises uuringus sooritasid jalgratturid töövõime testi kõrgeima hapnikutarbimise võime hindamiseks Tartu spordimeditsiinikeskuses Vomax, kasutades otsest gaasianalüüsi meetodit (MetaMax 3B, Cortex, Leipzig, Germany). Neil määrati enne, vahetult pärast ja 15 ning 30 min pärast konstantse koormusega jalgrattasõitu reie nelipealihase tahteline isomeetriline maksimaaljõud ning kontraktiilsed omadused dünamomeetriga. Jalgratturite istekoormuse jaotuvuse hindamiseks kasutati enne ja pärast koormust mõõteseadet (ConforMat; Tekscan Inc., Boston, MA, USA), mis registreeris surve jalgratturi ja istepinna vahel. Jalgratturid sooritasid 30-min submaksimaalse konstantse intensiivsusega jalgrattasõidu, mis viidi läbi koormusel 50% maksimaalsest võimsusest Cyclus-2 ergomeetril (Avantronic, Cyclus 2, Leipzig, Germany) isikliku jalgrattaga. Koormuse vältel olid vaatlusaluse kümnele lihasele bilateraalselt kinnitatud EMG elektroodid (*m. erector spinae* L3 kõrgusel, *m. gluteus medius*, *m. biceps femoris*, *m. vastus lateralis* ning *m. rectus femoris*), mis registreerisid lihasaktiivsust vastavates lihastes elektromüograafi ME6000 (Kuopio, Finland) abil.

Uuringus osalejad allkirjastasid kirjaliku nõusoleku uuringus osalemiseks ning uuring oli heaks kiidetud Tartu Ülikooli inimuuringute eetikakomitee poolt (nr 217/T-3).

Järeldused

1. Meessoost maanteejalgratturitel ilmnesid tugevamad seosed luutiheduse näitajate ja kehamassi vahel võrreldes mittetreenitud meestega, sealjuures olulisi seoseid reie nelipealihase tahtelise maksimaaljõu ning keha koostise ja luutiheduse näitajate vahel jalgratturitel ei esinenud.
2. Meesratturitel ilmnes konstantse koormusega jalgrattasõidu järgselt reie nelipealihase tahtelise maksimaaljõu langus koos perifeerse väsimuse tekkega.
3. Reie nelipealihase elektrostimulatsiooniga esile kutsutud üksikkontraktsiooni näitajad taastusid pärast 30-min konstantse koormusega jalgrattasõitu kiiremini võrreldes tahtelise maksimaaljõuga.
4. Konstantse submaksimaalse koormusega 30-min jalgrattasõidu ajal ilmnes meesratturitel seljalihaste märkimisväärne väsimine, hinnatuna lihaste aktivatsiooni sageduse languse alusel.
5. Meesratturitel ilmnes konstantse submaksimaalse koormusega jalgrattasõidu järgselt oluline asümmeetria isteasendis survejõudude jaotuvuses istmikuluude piirkonnas.

Praktiline väärtus:

Närvi-lihassüsteemi adaptatsiooni hindamine submaksimaalse koormusega jalgrattasõidu tingimustes annab vajalikku informatsiooni jalgratturi hetkeseisundi kohta ning ka jalgratturi sooritusvõime parandamiseks väsimuse tingimustes. Survejõudude jaotuvuse hindamine isteasendis enne ja pärast koormust on kindlasti üheks lisavõimaluseks ennetamaks ülekoormusprobleemide arenemist ülekoormusvigastuseks, eelkõige just pikaajalise konstantse koormuse tulemusena.

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PUBLICATIONS

CURRICULUM VITAE

Name:	Laura Lepasalu
Date of birth:	July 29, 1986, Tartu
Citizenship:	Estonian
Address:	Institute of Sport Sciences and Physiotherapy, Ujula 4, Tartu, 51008
Telephone:	+372 516 9134
E-mail:	laura.lepasalu@ut.ee

Education

2011–…	University of Tartu, Faculty of Medicine Doctoral study in Exercise and Sport Sciences (PhD)
2009–2011	University of Tartu, Faculty of Exercise and Sport Science Master of Science in Physiotherapy (MSc)
2005–2009	University of Tartu, Faculty of Exercise and Sport Sciences Bachelor of Physiotherapy (BA)
2002–2005	Tartu Mart Reiniku Gymnasium
1993-2002	Tartu Veeriku School

Professional employment

2023–…	University of Tartu, Faculty of Medicine, Institute of Sport Sciences and Physiotherapy, visiting lecturer
2023–…	Liikumistervis OÜ, founder, physiotherapist
2010–2022	Mustimets OÜ, physiotherapist
2010–2015	Estonian Cyclists Union, physiotherapist
2015	Bora-Argon 18, pysiotherapist
2014	Pro Cycling Team Astana, physiotherapist
2013	University of Tartu, Faculty of Exercise and Sport Sciences, Institute of Exercise Biology, Chair of Kinesiology, assistant
2012	Champion System Pro Cycling Team, physiotherapist
2010–2011	Estonian Agrenska Foundation, physiotherapist
2010–2011	Tartu Kindergarten “Nukitsamees”, physiotherapist
2007–2008	Tartu University Academic Sports Club, cycling coach

Main research interests: musculoskeletal disorders, physical activity, kinesiology, sports performance.

ELULOOKIRJELDUS

Nimi: Laura Lepasalu
Sünniaeg: 29. juuli 1986, Tartu
Kodakondsus: Estonian
Aadress: Sporditeaduste ja füsioteraapia instituut, Ujula 4, Tartu, 51008
Telefon: +372 516 9134
E-mail: laura.lepasalu@ut.ee

Haridus

2011–…	Tartu Ülikool, Meditsiiniteaduste valdkond, Sporditeaduste ja füsioteraapia instituut. Liikumis- ja sporditeaduste doktoriõpe
2009–2011	Tartu Ülikool, Kehakultuuriteaduskond. Magistrikraad füsioteraapias (MSc)
2005–2009	Tartu Ülikool, Kehakultuuriteaduskond. Bakalaureusekraad füsioteraapias (BA)
2002–2005	Tartu Mart Reiniku Gümnaasium
1993-2002	Tartu Veeriku Kool

Töökogemus

2023–…	Tartu Ülikool, Meditsiiniteaduste valdkond, Sporditeaduste ja füsioteraapia instituut, külalislektor
2023–…	Liikumistervis OÜ, asutaja, füsioterapeut
2010–2022	Mustimets OÜ, füsioterapeut
2010–2015	Eesti Jalgratturite Liit, füsioterapeut
2015	Bora-Argon 18 jalgratturite profitiim, füsioterapeut
2014	Astana jalgratturite profitiim, füsioterapeut
2013	Tartu Ülikool, Kehakultuuriteaduskond, Spordibioloogia ja füsioteraapia instituut, kinesioloogia õppetool, õppeassistent
2012	Champion System jalgratturite profitiim, füsioterapeut
2010–2011	Eesti Agrenska Fond, füsioterapeut
2010–2011	Tartu Lasteaed Nukitsamees, füsioterapeut
2007–2008	Tartu Ülikooli Akadeemiline Spordiklubi, jalgrattaspordi treener

Peamised uurimisvaldkonnad: luu- ja lihaskonna vaevused, kehaline aktiivsus, kinesioloogia, spordifüsioteraapia.

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