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## Multisite electromyographic analysis of quadriceps muscle during exerciserelated fatigue, pain and recovery

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**SMI** CENTER FOR SENSORY- MOTOR INTERACTION

**Multisite Electromyographic Analysis of Quadriceps Muscle During Exercise-related Fatigue, Pain and Recovery**

CENTER FOR SENSORY- MOTOR INTERACTION (SMI)  
DEPARTMENT OF HEALTH SCIENCE AND TECHNOLOGY

AALBORG UNIVERSITY

2008

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## Table of contents

Abbreviations used in the thesis.....	1
Preface.....	2
Acknowledgments.....	3
Abstract .....	4
Introduction .....	5
1. Fatigue and DOMS in the quadriceps .....	7
1.1 Quadriceps muscles .....	7
1.2 Quadriceps adaptations to eccentric exercise .....	8
1.3 Fatigue .....	9
1.3.1 Force and muscle fatigue .....	9
1.3.2 Location dependency of muscle fatigue .....	10
1.4 DOMS.....	11
1.4.1 Definition and time course.....	11
1.4.2 Distribution of DOMS.....	11
1.5 Effect of muscle injury on muscle fatigue .....	12
1.6 Motor control and sensory changes after eccentric exercise.....	13
2 Methods.....	15
2.1 Multi-channel surface EMG.....	15
2.2 Intramuscular EMG.....	16
2.3 Force recordings.....	17
2.4 Eccentric exercise protocol.....	18
2.5 Pain assessment.....	18
3 Summary of the studies.....	20
3.1 Study I.....	20
3.2 Study II.....	20
3.3 Study III.....	20
3.4 Study IV.....	21
3.5 Study V.....	21
4 General discussion and conclusion.....	23
References.....	25

## Abbreviations used in the thesis

ARV	Average rectified value
ASIS	Anterior superior iliac spine
Ca <sup>+</sup>	Calcium
Cl-	Chloride
CV	Conduction velocity
DOMS	Delayed onset muscle soreness
EC	Excitation –contraction
EMG	Electromyography
H <sup>+</sup>	Hydrogen
K <sup>+</sup>	Potassium
MPF	Mean power spectral frequency
MUAP	Motor unit action potential
MVC	Maximal voluntary contraction
Na <sup>+</sup>	Sodium
Pi	Inorganic phosphate
PPT	Pressure pain threshold
RF	Rectus femoris
SMU	Single motor unit
SR	Sarcoplasmic reticulum
VAS	Visual analogue scale
VL	Vastus lateralis
VI	Vastus intermedius
VM	Vastus medialis
VMO	Vastus medialis oblique

## **Preface**

The Ph.D. thesis is based on the five studies performed at the Center for Sensory-Motor Interaction (SMI), Aalborg University, Denmark, in the period 2004 to 2008:

**Study I:** Hedayatpour N, Arendt-Nielsen L, Farina D (2007) Motor unit conduction velocity during sustained contraction of the vastus medialis muscle. *Exp Brain Res* 180 (3):509-16 , DOI 10.1007/s00221-007-0877-4

**Study II:** Hedayatpour N, Arendt-Nielsen L, Farina D (2008) Non-uniform electromyographic activity during fatigue and recovery of the vastus medialis and lateralis muscles. *J Electromyogr Kinesiol* 18:390-6, DOI:10.1016/j.jelekin.2006.12.004

**Study III:** Hedayatpour N, Falla D, Arendt-Nielsen L, Farina D (2008) Sensory and electromyographic mapping during delayed-onset muscle soreness. *Med Sci Sports Exerc* 40(2):326-34, DOI: 10.1249/mss.0b013e31815b0dcb

**Study IV:** Hedayatpour N, Falla D, Arendt-Nielsen L, Farina D. Effect of delayed onset muscle soreness on muscle recovery after a fatiguing isometric contraction (2008) *Scand J Med Sci Sports* [Epub ahead of print], DOI: 10.1111/j.1600-0838.2008.00866.x

**Study V:** Hedayatpour N, Falla D, Arendt-Nielsen L, Carolina Vila-Chã, Farina D. Motor unit conduction velocity during sustained contraction of the vastus medialis muscle injured by eccentric contractions. Submitted (2008)

## **Acknowledgments**

I would like to express my gratitude to my supervisor, Professor Dario Farina. We had extremely profitable scientific conversions during my Ph.D study in Denmark. He was always ready and present to discuss and point out precise comments on the Ph.D project and execution. I can not imagine any better supervisor than Dario is. I certainly would like to express my sincere thank to Professor Lars Arendt –Nielsen and Associate Professor Deborah Falla for their enthusiastic supervision. Both of them made a great contribution to all my studies. The Administrator Peter Thonning, and the Secretaries Ann Schmidt, Birgitte Kudal Hansen, Susanne Nielsen and the technical staff always offered great help. PhD student Mogens Nielsen is acknowledged for his contribution to the experiments and Danish translation. All the colleagues and volunteers in the experiments are also acknowledged.

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### Abstract

The quadriceps femoris muscle plays an important role in explosive and powerful actions of the leg during sport and daily activities. Eccentric contraction is commonly used during training programs because this contraction type is more effective than concentric contraction for increasing muscle force. However, eccentric exercise of the quadriceps is associated with fiber injury and delayed onset muscle soreness (DOMS) and therefore may reduce the ability of the quadriceps to stabilize the knee joint. This may expose structures of the knee to abnormal loading during exercise. There is indeed anecdotal evidence for patella injuries following training. It is currently not known whether the injury developed during eccentric exercise preferentially affects specific areas in the quadriceps muscle. In this PhD project, it was hypothesized that the distribution of muscle fiber size and the architecture of the quadriceps muscle determine non-uniform changes in activity and fiber membrane properties during fatiguing contractions and non-uniform adaptations to eccentric-exercise induced DOMS. This PhD thesis is divided into five studies. Study I showed the effect of force on the reduction in muscle fiber conduction velocity at the level of single motor units during fatiguing contractions. Study II demonstrated that the change in the distribution of muscle activation during fatigue and recovery is not uniform. The vastus medialis oblique (VMO) showed a greater reduction in EMG amplitude and mean power frequency (MPF) during a fatiguing contraction and a larger increase in MPF during recovery. In Study III, eccentric exercise was associated with decreased pressure pain thresholds (PPT) and EMG amplitude at 24 h and 48 h post eccentric contractions. Among the quadriceps muscles, VMO was the one that showed the largest decrease in PPT and EMG amplitude. In Study IV, it was shown that DOMS suppressed the typical recovery trend of MPF following post eccentric fatiguing contractions. This effect was particularly large in VMO compared to the other parts of the quadriceps. Study V analyzed single motor unit conduction velocity during fatiguing contractions with DOMS. DOMS resulted in a larger decrease in conduction velocity during fatiguing contractions than in control conditions, particularly for VMO. In conclusion, during this PhD project, we demonstrated a non-uniform change in neural drive within the quadriceps regions during fatigue, with more pronounced changes for VMO. In the presence of DOMS, muscle activity and fiber conduction velocity decreased more for the VMO than for other quadriceps regions. These results indicate that VMO is substantially weakened with fatigue and further weakened when DOMS occurs together with fatigue. Therefore, care should be taken to prevent lateral dislocation of the patella, especially if training programs include a large number of heavily loaded eccentric contractions.



### Introduction

Skeletal muscle fatigue is an inevitable part of any exercise training. Fatigue is the result of many physiological adaptations to sustained contraction, which occur at different levels of the neuromuscular system (Gandevia 2001), such as the central nervous system (Bigland Ritchie 1984; Bigland Ritchie et al. 1978; Lombard 1892), spinal cord (Sabatier et al. 2006), neuromuscular junction (Krnjevic et al. 1958; Krnjevic et al. 1959; Murali et al. 1984), sarcolemma membrane (Juel et al. 2000), and peripheral mechanisms within the muscle (Merton 1954; Bigland Ritchie et al. 1978). Fatigue is characterized by force deficit (Edwards 1981), pain and muscle weakness (Abraham 1977) and inadequate muscle recovery from fatigue may lead to overuse injuries (McClean et al. 2001). After eccentric exercise the extent of muscle fatigue and thus muscle adaptations is greater than following other types of exercise (Hakkinen et al. 1998; Hortobagyi et al. 1998), since this contraction type is associated with ionic membrane permeability changes (McBride et al. 1994; McBride et al. 2000) which in turn act as prerequisite for muscle hypertrophy (Hather et al. 1991) via sodium [ $\text{Na}^+$ ] influx and stimulating protein synthesis (Goldspink et al. 1992). However the fiber injury developed during eccentric exercise also exposes the muscle to delayed onset muscle soreness (DOMS) and weakness (Newham et al. 1983), which may reduce the muscle ability to stabilize the joint structures. A decreased ability to generate force may be caused by the altered neural drive to muscle fibers due to pain (Cervero and Laird 1996), an alteration in fiber membrane properties (McBride et al. 1994) and/or by factors associated with fiber damage (Newham et al. 1983) such as inflammation and insufficient energy supply (Gollnick and King 1969) and calcium release. There is indeed anecdotal evidence for musculoskeletal disorders following intensive eccentric training (Messner et al. 1999). The quadriceps femoris plays an important role in explosive and powerful actions of the leg during sport and daily activities. Eccentric contraction is commonly used during training programs to improve muscular power for the quadriceps muscles (Jones and Rutherford 1987). Patellofemoral disorders have a high prevalence among people who are involved in eccentric exercise of the leg (Papagelopoulos and Sim 1997; Baker et al. 2002). The underlying mechanisms of the exercise-related patella disorders are not fully understood. It is currently not known whether the injury developed during eccentric exercise preferentially affects particular locations of the quadriceps and thus leads some regions of the quadriceps to become more fatigable and less active than others. Fatigue at the level of the muscle fiber membrane is related to increased extracellular potassium [ $\text{K}^+$ ] which in turn leads to reduced muscle fiber conduction velocity (CV) and force (Jones 1981). The extent of extracellular [ $\text{K}^+$ ] concentration during fatigue

is determined by the distribution of muscle fibre type (Juel 1986) and hydrogen  $H^+$  production (Davies et al. 1992; Caputo et al. 1984), which can be different within the quadriceps regions. Recovery of the excitation-contraction process at the level of the muscle fibers depends on the ability of the fiber membrane to counterbalance the ionic gradient between the two sides of the membrane (Lindinger and Sjogaard 1991; Lindinger 1995). Muscle fiber injury developed during eccentric exercise affects both muscle fatigability and the recovery process, due to pathophysiological changes in the muscle fiber (Armstrong 1984). Because of the relevance of muscle fatigue and recovery for the force a muscle can exert and because this force may be related to stabilization of joint structures which are prone to injury, it is relevant to analyze the effect of muscle damage induced by eccentric exercise on these processes.

### **Aim of the Ph.D studies**

The aim of this PhD project is to investigate changes in the distribution of muscle activation and fiber membrane properties during fatigue and recovery in normal conditions and during DOMS induced by eccentric-exercise.

The thesis covers of the following topics:

1. Assessment of the effect of force on the reduction of fiber membrane CV at the level of the single motor unit (SMU) during fatiguing contraction (Study I)
2. Evaluation of changes in the distribution of muscle activation and fiber membrane properties within the quadriceps during fatigue and recovery (Study II)
3. Assessment of fatigue and recovery in the quadriceps following eccentric-exercise induced DOMS at the global level (surface electromyography, EMG) (Study II, III and IV) and on individual motor units (Study I, V)

Figure 1 shows a schematic representation of the links among the five studies of this thesis.

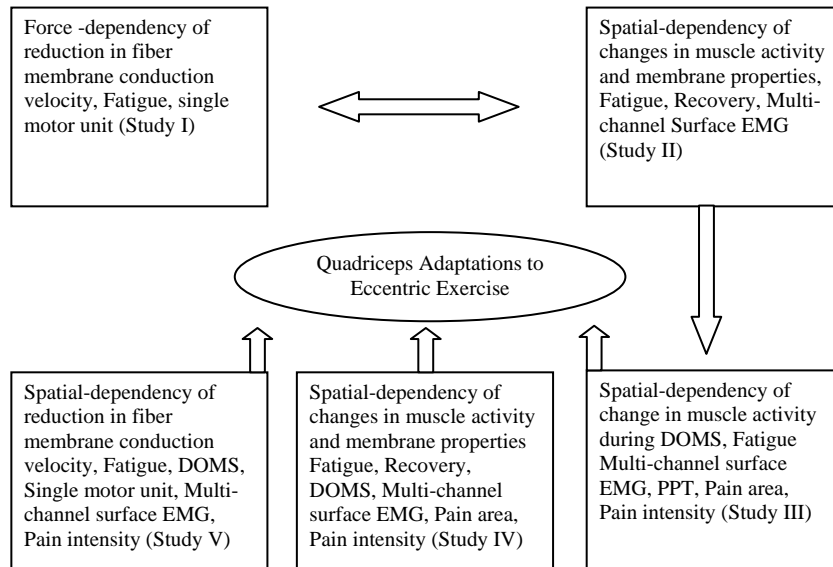


Figure 1. The composition of the present Ph.D study

## 1. Fatigue and DOMS in the quadriceps

### 1.1 Quadriceps muscles

The quadriceps femoris, as primary knee extensor, comprises four distinct components: the rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), and the vastus intermedius (VI) (Figure 2). The quadriceps muscles are characterized by a large variation in fiber-type composition (Elder et al. 1982), fiber orientation (Blazevich et al. 2006; Wickiewicz et al. 1983), and fiber length (Blazevich et al. 2006) within each muscle compartment that enable these muscles to contribute to an extensive range of activities such as stabilization of the patella, external/internal rotation of the tibia, and knee extension (Goodfellow and O'Connor 1978). Variation in morphological and architectural characteristics of the muscle fibers also implies a non-uniform vulnerability of the fibers to fatigue and damage (Friden et al. 1983; Takekura et al. 2001). In the current project, surface and intramuscular EMG signals were recorded from different locations of the quadriceps

components. This approach allows the investigation of the change in distribution of muscle activation and fiber membrane properties within the quadriceps after eccentric exercise.

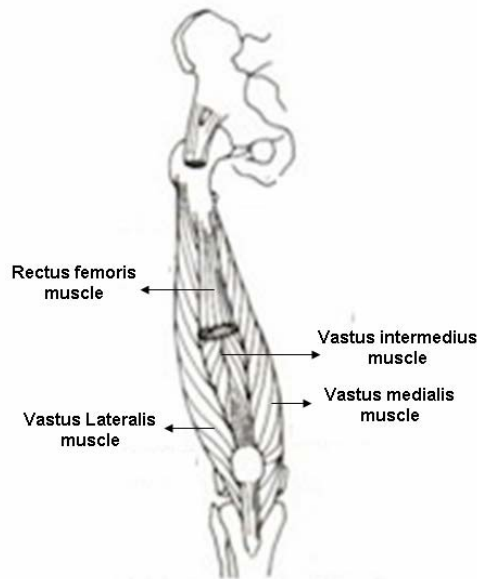


Figure 2. The quadriceps femoris muscle

### 1.2 Quadriceps adaptations to eccentric exercise

Quadriceps adaptations to eccentric exercise are characterized by symptoms and signs of weakness, inflammation, widespread pain, regional hyperalgesia, and increased ionic membrane permeability of the muscle fibers (Newham et al. 1987; Newham et al. 1983; McBride et al. 1994) due to fiber damage. Furthermore, a significant predominance of muscle soreness exists around the knee (Baquie and Bruckner 1997; Brody 1980; Macintyre et al. 1991). This may partly explain the effectiveness of eccentric contractions for inducing muscle hypertrophy (Hather et al., 1991) via  $[Na^+]_i$  influx and stimulating protein synthesis (Goldspink et al., 1992). However, an abnormal sarcolemmal membrane permeability would also shift the resting membrane potential of the damaged fibers towards depolarization due to increases in intracellular sodium  $[Na^+]_i$  and calcium  $[Ca^+]_i$ , and uptake of large molecular weight markers (McBride et al. 1994, McBride et al. 2000). This may have an effect on the capacity of the membrane to conduct action potentials for releasing  $[Ca^+]_i$  ions during a sustained voluntary contraction.

### 1.3 Fatigue

Muscle fatigue is an exercise-induced reduction in maximal voluntary muscle force, which may be the result of neural transmission failure at the level of the muscle fiber and/or central nervous system (Gandevia 2001). The failure to maintain force can also be due to weakening of the muscle fibers. The site of fatigue may lie within the central nervous system (metabolic products centrally inhibits the motoneuron pool via reflex circuitry; Bigland-Ritchie et al. 1986; Garland et al. 1988; Woods et al. 1987), neuromuscular junction (presynaptic/postsynaptic inhibition of signal transmission, Sieck and Prakash 1995), and within the muscle fibers itself (low intracellular pH cause alterations in membrane function and prevent cell activation; Caputo et al. 1984; Caputo et al. 1981; Davies et al. 1992; Dulhunty 1983). Despite considerable research, the causes of muscle fatigue have yet to be clearly established. The problem is complex, since multiple factors are clearly involved; the relative importance of each factor depends on the fiber type composition of the contracting muscle, the intensity, type, and duration of the contractile activity, and the degree of fitness (Fitts et al. 1981). Fatigue experienced in high-intensity short-duration exercise relies mainly on anaerobic metabolism which in turn leads to an increase in intracellular hydrogen  $[H^+]$  and inorganic phosphate  $[Pi]$ , factors known to reduce maximal force (Donaldson and Hermansen 1978; Fabiato and Fabiato 1978; Hermansen 1979). In contrast, during prolonged submaximal exercise, cell energy is derived primarily from aerobic metabolism and, consequently, the muscle lactate,  $[H^+]$ , and  $Pi$  contents remain relatively unchanged (Saltin and Karlsson 1985), while the depletion of muscle glycogen and, in some cases, low blood glucose appear to be important contributing factors (Coyle 1991; Gollnick 1988).

#### 1.3.1 Force and muscle fatigue

Muscle fatigue is frequently associated with changes in the intracellular action potential, characterized by reduced amplitude, prolonged duration, and decreased CV (Benzanilla 1972; Lannergren and Westerblad 1986; Jones 1981). The resting membrane potential of skeletal muscle is largely a  $[K^+]$  dependent potential (Hodgkin and Horowitz 1959); thus any change in the  $[K^+]$  conductance or concentration gradient across the sarcolemma will affect the membrane CV (Figure 3). It has been shown that fatigue in both mammalian and frog muscle is associated with a loss of intracellular potassium  $[K^+]_i$  and a gain in chloride  $[Cl^-]$ ,  $[Na^+]$ , and water. The extent of the ion and water shifts is greater in large fast-twitch compared with small slow twitch motor units (Juel 1986) and increases with stimulation frequency and muscle activity (Fenn and Cobb 1936; Hodgkin

and Horowitz 1959). The orderly recruitment of motor unit with increasing twitch force has been well documented (size principle, Henneman 1957). With increasing force, changes in electrophysiological membrane properties and CV of muscle fibers were also observed by the analysis of the interference EMG signal (Knaflitz et al. 1990; Hogrel 2003; Masuda and De Luca 1991 ) and single motor units (SMU) (Masuda and De Luca 1991; Hogrel 2003, Farina et al. 2004). With increasing force, high threshold, large motor units are progressively recruited and this leads to progressively higher production of extracellular  $[K^+]$  and greater reduction in fiber membrane CV.

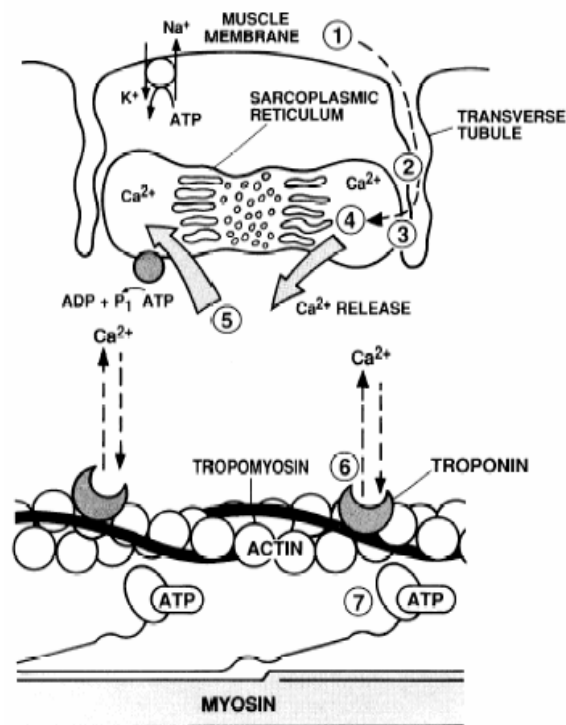


Figure 3. Schematic representation of the major components of a muscle cell involved in excitation-contraction coupling and fatigue [with permission From Karger S and Basel AG]

### 1.3.2 Location –dependency of muscle fatigue

It is well documented that the quadriceps components are characterized by varying fiber pennation angles and fiber-type composition, depending on the location within the muscle (Elder et al. 1982; Wickiewicz et al. 1983; Travnik et al. 1995; Blazevich et al. 2006). Muscle tension primarily depends on morphological and architectural features of muscle fibers (Coyle et al. 1979; Ichinose et

al. 1998). This implies that the performance of a task requires a preferential activation of different muscle parts (Kinugasa et al. 2005a, 2005b, 2006a, 2006b) and non-uniform metabolic accumulation, thus site-specific muscle fatigue and recovery. Non-uniform pattern of tension and muscle activation within the skeletal muscle has been reported using integrated electromyography (iEMG) activity (Adams et al. 1992; Kinugasa et al. 2005a), force induced by electrical stimulation (Adams et al. 1993), and voluntary contraction (Adams et al. 1992; Kinugasa et al. 2005a). Accordingly, a non-uniform distribution of EMG activity has been also observed over muscles during sustained contraction (Li and Sakamoto 1996; Holtermann et al. 2005).

### 1.4 DOMS

#### 1.4.1 Definition and time course

DOMS usually occurs as result of pathophysiological changes in the muscle fibers within 24 and 48 hours after eccentric exercise (Armstrong 1984) and manifests as a dull, aching pain combined with tenderness and stiffness (Armstrong 1984; Bajaj et al. 2001; Dannecker et al. 2003; Ebbeling and Clarkson 1989). It usually lasts 5 to 7 days post exercise (Nosaka and Clarkson 1996; Stauber 1996). In the studies conducted in this thesis, DOMS peaked at 24 hours and persisted 48 hours following eccentric task (Study III, IV and V). No significant differences were found between 24 and 48 hours post exercise. This is in agreement with previous results on the quadriceps and others muscles (Newham et al. 1987; Newham et al. 1983).

#### Distribution of DOMS

Tenderness is one of main symptoms of DOMS which is characterized by a reduction in pain threshold to normally innocuous mechanical stimulation (LaMotte et al. 1991). The pain and tenderness associated with DOMS has been attributed to sensitization of intramuscular nociceptors from algescic substances released subsequent to muscle damage (Newham et al. 1983, 1986). A significant decrease in pressure pain threshold (PPT) was found on quadriceps indicated that this

muscle was affected by high tension eccentric exercise (Newham et al. 1983). With regards to the large variations in muscle fiber properties within the quadriceps components (Elder et al. 1982; Wickiewicz et al. 1983), it is expected that eccentric exercise results in non uniform fiber damage and, as a consequence, non uniform sensory and motor control changes. However, previous to this thesis, no studies have investigated spatial variations in muscle activity during sustained contraction of the quadriceps components injured by eccentric exercise. A few studies have discussed the manifestation and distribution of tenderness on the quadriceps and others muscles. The initial tenderness has been reported to be located in the distal, lateral and medial part of the quadriceps, but at the peak intensity of soreness the muscle tendon region was not more prone to soreness than others muscle sites (Newham et al. 1983). Barker et al. (1997) reported a lower pressure pain tolerance in myotendinous sites of the quadriceps than in the muscle belly after eccentric down-hill running. However, in the same study the PPTs were more reduced at the muscle belly than at myotendinous sites when DOMS reached to the peak level. Accordingly, a non uniform distribution of tenderness has been also reported in other muscles of the upper and lower extremities (Cleak and Eston 1992; Bobbert et al. 1986).

### **1.5 Effect of muscle injury on muscle fatigue**

The development of fatigue and pain depends on the nature of the muscle contraction. Furthermore, two types of soreness have been described; one occurring during maintained contractions and closely associated to fatigue and a second type that generally occurs after exercise and persists for a prolonged period of time (Hough 1902). The former is a result of metabolic waste products in which the soreness is elicited by tissue swelling or a direct chemical stimulation of muscle afferents (Crow and Kushmerick 1982). This type of soreness rapidly reverses following exercise. In contrast, the latter post exercise type of soreness was associated to rhythmic contractions and has its origin in the damage of the muscle fibers (Armstrong 1984). It has been demonstrated that eccentric contractions but not concentric or isometric contractions can induce muscle injury (Armstrong et al. 1983; Friden J and Lieber 1992; Newham et al. 1983). An eccentric contraction occurs when a muscle is contracting, while an external force is trying to lengthen the muscle. Damage to muscle fiber during eccentric exercise is substantiated by preferential recruitment of fast twitch fibers (Nardone et al. 1989), less motor unit activation per tension level (Komi et al. 1987; Tesch et al. 1990), and producing maximum force on the weakest point of muscle length (Brockett et al. 2004; Gleeson et al. 2003). DOMS have been reported in lower (Fridén et al. 1981; Baker et al. 1997) and



upper extremities (Nie et al. 2005) after eccentric exercise. The time course of muscle fiber injury and therefore its contribution to muscle fatigue depends on the type of eccentric exercise. With high-intensity exercise, the high-force contractions initiate injury early in the exercise period. In this type of exercise, the causative event is the mechanical disruption of the sarcomeres and perhaps the sarcolemma membrane (Friden and Lieber 1992; Lieber et al. 1991), which in turn further contributes to fiber degradation via influx of  $[Ca^{+}]$  and the activation of cell proteases and phospholipase activity (Armstrong et al. 1991; Duncan 1987). In contrast, the contractions associated with prolonged endurance activity are less forceful and less likely to cause a direct mechanical disruption of the muscle cell. In this type of activity, the possibility exists that the injury process develops late in the exercise period through inhibition of the sarcoplasmic reticulum (SR) function and buildup of cytosolic  $[Ca^{+}]$  (Armstrong et al. 1991). The observation that isometric strength was lowest immediately after high intensity eccentric protocol of this PhD project, indicates that the injury developed during the exercise and contributed to the fatigue process. In accordance with previous published literature, it was also observed that the degree of muscle injury becomes progressively worse in the first few days after intense eccentric exercise (Prasartwuth et al. 2005), as subjectively reported by pain scores on a visual analog scale (VAS) during their regular activities of daily living (e.g., climbing stairs). This observation explains why performance can remain depressed for days after eccentric exercise even though all the known fatigue agents (lactic acid,  $[Pi]$ , creatinine etc...) have recovered (Harris et al. 1976).

### **1.6 Motor control and sensory changes after eccentric exercise**

It has been shown that patterns of muscle activation and motor unit recruitment are altered in the presence of pain (Hodges and Richardson 1996). These phenomena have been shown to persist into the period of chronicity (Hodges and Richardson 1996; O'Sullivan et al. 1997; Hides et al. 1994; Hides et al. 1996). DOMS has been shown to decrease muscle activation as reflected by reduction of EMG activity during post eccentric sustained isometric contraction (Hagberg and Hagberg 1989; Pincivero et al. 2006). This phenomenon is in agreement with the pain adaptation model, in which pain effects the muscle activation by inhibition of the agonist muscle and excitation of the antagonist muscle that results in a reduced force production (Lund 1991). The reduced muscle activation may be caused by abnormal afferent input from damaged and inflamed tissue of the injured muscle (Hurley 1997; Johansson and Sojka 1993; Mense and Skeppar 1991; Hulliger 1984) which affects the excitability of alpha and gamma motor neurons (Figure 4). Changes in the

## Introduction

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behaviour of spinal cord neurons after a barrage of nociceptive input mediated by inflammatory factors, can be maintained as result of the actions of protective or disused muscles (Zusman M 1997) and/or phenotype changes in large diameter, myelinated afferent neurons that allow them to induce central sensitization in the same manner as unmyelinated C fibers (Woolf and Costigan 1999). This can provide a major source of posthealing pain and an ongoing stimulus for the changes in motor function and probably can be a potential source for subsequent musculoskeletal disorders. Moreover, the sarcolemma is also subjected to substantial tears during eccentric contractions (Petrof et al. 1993; McNeil and Khakee 1992). This would probably increase sarcolemmal membrane permeability to ions such as  $[Na^+]_i$  and  $[Ca^+]_i$ , which in turn leads to membrane depolarization (McBride et al. 1994; McBride et al. 2000) and reduced CV (Jones et al. 1981).

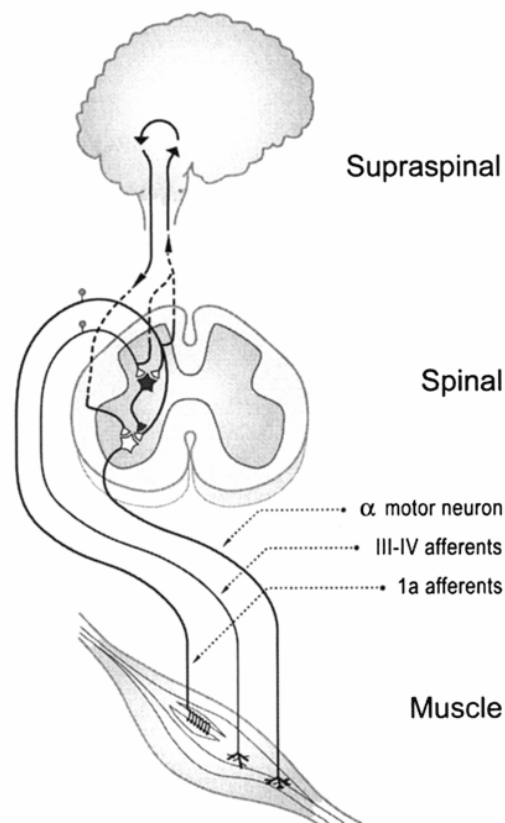


Figure 4. Schematic representation of the inhibitory pathways that mediate input from inflamed tissue of the injured muscle to the spinal cord [Source: Exerc Sport Sic Rev]

In the following, the methods used in the five studies of this PhD project are describe

## 2. Methods

### 2.1 Multi-channel surface EMG

Multi-channel surface EMG as a non-invasive method has commonly been used to investigate muscle activity and fiber membrane properties changes in different disciplines, such as exercise physiology (Clarys and Cabri 1993), neurology (Fasshauer 1981) ergonomics (Koh and Grabiner 1992 ), and rehabilitation (Flor and Turk 1989). The multichannel approach has been based on increasing the number of electrodes placed over the muscle in order to obtain a map of the potential distribution over the skin surface rather than a single observation (Figure 5). The use of multichannel surface EMG allows to concomitantly detect bipolar EMG derivations from a number of locations over the muscle and thus leads to a global sampling of surface potential distribution (Drost et al. 2001; Hunter et al. 1987). It has been reported that sampling of the action potentials generated in different points along the muscle also provide information about the innervation zone, the length of muscle fiber, muscle fiber CV , and abnormalities in action potential propagation (Masuda et al. 1983; Drost et al. 2001), which can not be extracted by a single pair of electrodes. In the current Ph.D project (Studies I, II, and V), an adhesive linear array of eight equi-spaced electrodes (bar electrodes 5-mm long, 1-mm diameter, 5-mm inter-electrode distance; developed by Politecnico di Torino, Italy) was used to detect surface EMG signals. The array was located between the most distal innervation zone and the distal tendon region of the muscle. The skin was lightly abraded in the location selected for array placement. To assure proper electrode-skin contact, 20  $\mu$ l of conductive gel were inserted into the cavities of the adhesive electrode array. CV of single motor units (Study I and IV) was estimated from each averaged surface potential by a multi-channel technique previously described (Farina et al. 2001). The method estimates the delay that best aligns the set of propagating signals, according to a mean square error measure of shape similarity. It has been shown that this method allows detection of small changes in conduction velocity (in the order of 0.1–0.2 m/s) (Farina et al. 2002) and that it is less sensitive to tissue in-homogeneities than classic two-channel approaches (Farina and Mesin 2005). Average rectified value (ARV) and mean power spectral frequency (MPF) were estimated from the surface EMG signals in Study I, II, III, and IV. Bipolar surface EMG signals were detected in Study III and IV. In all studies, surface EMG signals were amplified (EMG16, LISiN–Ottino Bioelettronica, Torino, Italy, bandwidth 10–500 Hz), sampled at 2.048 Hz, and stored after 12-bit A/D conversion.

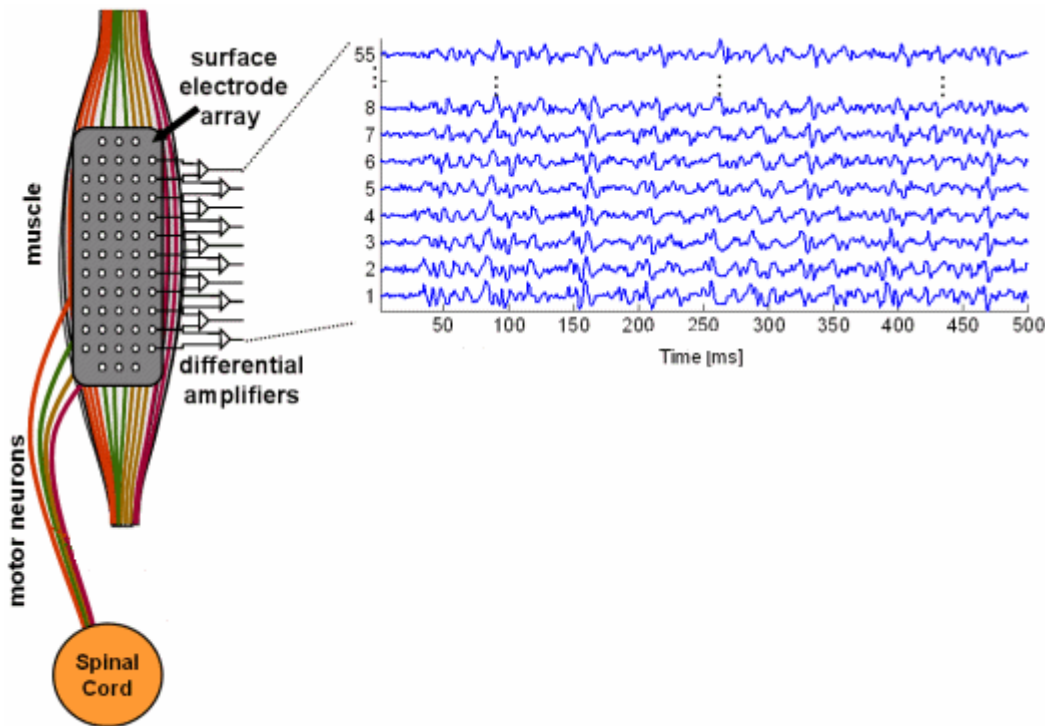


Figure 5. Schematic representation of surface EMG signal generation (left) and acquisition (right) [With permission from Holobar A and Zazula D]

## 2.2 Intramuscular EMG

The intramuscular EMG recording technique is classically used to study the physiology and pathology of the motor unit (Figure 6). Some techniques, such as spike-triggered averaging, combine the advantages of the intramuscular and surface detection by using the first to detect and classify motor unit action potentials (MUAPs) and the second to estimate features of motor units associated to such MUAPs (Stein et al. 1972). In this PhD project, two wire electrodes made of Teflon coated stainless steel (A-M Systems, Carlsborg, WA, USA) were inserted with a 23 G needle, 10–20 mm proximal to the surface array top, in line with the direction of the array (Study I and V). The wires were un-insulated for ~1 mm at the tip and bent in the insertion needle. The depth of needle insertion was of a few millimeters below the muscle fascia. The needle was removed with the wire electrodes left inside the muscle. The signal with the highest signal-to-noise ratio was used for decomposition. The times of occurrence of the intramuscular action potentials were used as triggers for averaging the multi-channel surface EMG signals (20 triggers in all cases). Intramuscular EMG signals were amplified (DANTEC Counterpoint electromyograph, DANTEC

Medical A/S, Skovlunde, Denmark), band-pass filtered (500 Hz–5 kHz), sampled at 20,480 Hz, and stored after 12-bit A/D conversion.

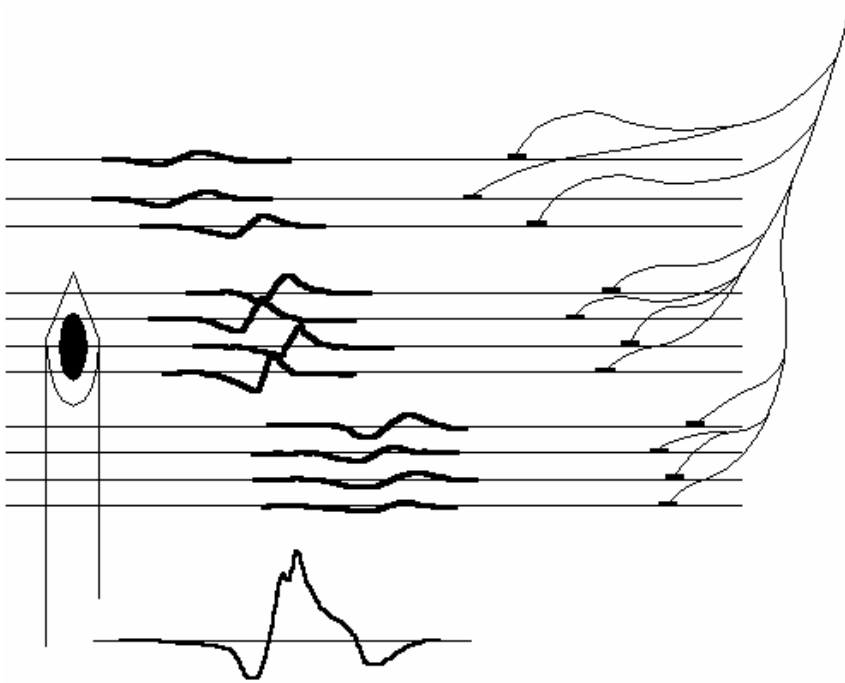


Figure 6. Motor unit action potential (MUAP) as detected by a concentric needle electrode [With permission from Hammarberg HB and Sternad M]

### 2.3 Force recordings

The KinCom Isokinetic Dynamometer (Chattanooga, TN, USA) measured the force around the knee joint (Studies III, IV, and V) (Figure 7). The chair position was adjusted until the knee axis of rotation (tibiofemoral joint) was aligned with the axis of rotation of the dynamometer's attachment arm. The subject was asked to perform three maximal isometric knee extensions (3-5 s in duration) in 90° knee flexion, with 2 min of rest between, and verbal encouragement to exceed the previous force level. The highest maximal voluntary contraction (MVC) value was used as a reference for the definition of the submaximal force level. The submaximal forces were relative to the MVC measured on the same day of the test. This signal was used to provide feedback on the exerted joint force on a screen positioned in front of the subject during sustained contractions. Task failure during sustained contractions was defined as a drop in force greater than 5% MVC for more than 5 s after strong verbal encouragement to the subject to maintain the target force (Studies III and IV). The force signal was sampled at 2048 Hz and synchronized with the surface and intramuscular EMG signal recordings.

### 2.4 Eccentric exercise protocol

DOMS was induced in Studies III, IV and V. The eccentric exercise was performed with a KinCom Isokinetic Dynamometer (Chattanooga, TN, USA) (Figure 7) and consisted of four bouts of 25 maximum voluntary concentric/eccentric knee extension contractions at a speed of  $60^{\circ}\cdot\text{s}^{-1}$  between  $90$  and  $170^{\circ}$  of knee extension, with 3 min of rest between each set. During the exercise, the subject was provided with visual feedback of force and was encouraged to maintain maximal force.

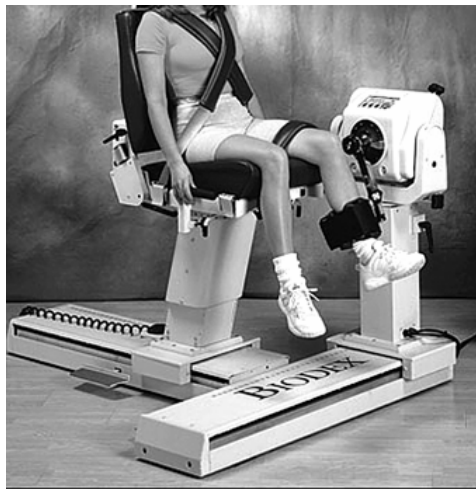


Figure 7. The KinCom Isokinetic Dynamometer (Chattanooga, TN, USA)

### 2.5 Pain assessment

Pain was subjectively assessed in the studies on DOMS (Studies III, IV, and V). Pain is a subjective multidimensional perception, since the perception of pain can be affected by many psychological and social factors (Turk et al. 2002). Therefore the reaction to a single standardized experimental stimulus of a given modality can only represent a very limited fraction of the entire pain experience (Graven-Nielsen and Arendt-Nielsen 2003). Psychophysical methods such as stimulus-dependent method have been widely used to assess the perceived pain (Graven-Nielsen and Arendt-Nielsen 2003). The stimulus-dependent method is based on the adjustment of the stimulus intensity until a predefined response is reached. Graded increased pressure by algometer is the kind of method which was used to test pain threshold in this project (Study III). The PPT is a useful index in evaluating the tenderness of musculoskeletal structures (Antonaci et al. 1998; Persson et al. 2004). The VAS is commonly used as a valid instrument in pain rating in clinical and experimental

## Methods

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conditions (Price et al. 1983). In this project (Studies III, IV, and V), VAS was used to assess the perceived pain intensity during regular activities of daily living (e.g., climbing stairs) at 24 and 48 hours after eccentric exercise. The passive range of knee flexion was measured with a goniometer and participants were also asked to document the area of pain on a body chart. Pain drawings were subsequently digitized (ACECAD D9000+ Taiwan), and pain areas were estimated in arbitrary units for comparison among days.

### 3. Summary of the studies

#### 3.1 Study I

Motor unit CV during 180-s long contractions at forces in the range 2.5-30% of MVC was analyzed in the distal part of the VM muscle by surface (8-electrode array) and intramuscular (two wire electrodes) EMG recordings. Muscle fiber CV has frequently been used as an indicator of motor unit size (Andreassen and Arendt-Nielsen 1987) and muscle fiber membrane fatigue (Farina et al. 2005) during isometric contractions. The present study showed a relation between CV, ARV, and recruitment threshold also in case of constant discharge rate of the analyzed motor units. Average CV of the active motor units showed faster rate of decrease over time with increasing force (Merletti et al. 1990) probably due to high production of extracellular  $[K^+]$  as result of increasing the number of active motor unit (Jones 1981; Juel 1986; Thompson et al. 1992).

#### 3.2 Study II

EMG signal features were investigated at 10%, 20%, and 30% of the distance from the medial (for vastus medialis) and lateral (vastus lateralis) border of the patella to the anterior superior iliac spine (ASIS) during fatigue and recovery at 40% and 80% MVC. A spatial dependency of EMG variables (EMG amplitude and MPF) was observed for the quadriceps muscles during fatigue and muscle recovery probably due to variations in morphological and architectural characteristics of muscle fibers and thus non-uniform metabolic by-production within the muscle. The vastus medialis oblique (VMO) showed a greater reduction in EMG amplitude and MPF during a fatiguing contraction and a larger increase in MPF during recovery, which may be related to fiber type composition and/or higher activation of this region to overcome the strong lateral pull of the VL muscle on the patella.

#### 3.3 Study III

Fifteen sets of bipolar electrodes were applied to investigate EMG manifestations of DOMS at 10, 20, 30, 40, and 50% of the distance from the medial, superior, and lateral border of the patella to ASIS during 40% maximal knee isometric extension. After eccentric exercise, a significant reduction in muscle force, time to task failure and a greater decrease in EMG amplitude over time



were observed during the sustained isometric contraction. An inhibitory effect mediated by pain was in agreement with the decrease in EMG amplitude (Weerakkody et al. 2001) for the VMO, which were the areas with larger reduction in PPT. Selective inhibition of specific muscle portions may be related to a site-specific production of inflammatory agents (e.g., prostaglandins) or neuromuscular disruption in response to eccentric exercise, which in turn block signal transmission to varying degrees, depending on the location within the muscle.

### 3.4 Study IV

Bipolar surface EMG signals were recorded from six locations distributed over the quadriceps during the sustained isometric contraction and during recovery (3-s long contractions) at 40% MVC before and after eccentric exercise. The electrodes were located at 10%, 20%, and 30% of the distance from the medial and lateral border of the patella to the ASIS. Recovery of the excitation-contraction process at the level of the muscle fibers depends on the ability of the fiber membrane to counterbalance the ionic gradient between the two sides of the membrane after fatiguing contractions (Lindinger and Sjogaard 1991; Lindinger 1995). In this study a significant reduction in EMG mean frequency was observed during recovery following post eccentric fatiguing contraction, which may indicate a reduced capacity of  $\text{Na}^+ - \text{K}^+$  ATPase and/or membrane ionic permeability changes in the damaged fiber after unaccustomed exercise. Among the quadriceps muscles, VMO showed the largest decrease in EMG mean frequency.

### 3.5 Study V

Surface and intramuscular EMG signals were simultaneously recorded from the VM muscle at 10% and 30% (distal, proximal) of the distance from the medial border of the patella to the ASIS, during pre- and post eccentric sustained knee isometric extensions at 10% and 30% MVC. Failure in EC coupling pathways has been reported as a primary mechanism of the force deficit following eccentric exercise induced DOMS (Warren et al. 1993; Balnave and Allen 1995; Ingalls et al. 1998). The sarcolemma is subjected to substantial tears during eccentric contractions (Petrof et al. 1993; McNeil and Khakee 1992). In the present study, single motor unit CV showed a greater rate of reduction during a post-eccentric exercise sustained fatiguing contraction, which may indicate an alteration in resting membrane potential of the damaged fibers (McBride et al. 1994; McBride et al. 2000). The VMO was more affected which may be related to fiber type composition (Travnik et al.

1995) and/or high force production of this region to stabilize the patella during high intensity eccentric exercise (Sakai et al. 2000).

### 4. General discussion and conclusions

The quadriceps femoris muscle plays an important role in explosive and powerful actions of the leg during sport and daily activities. Eccentric contraction is commonly used during training programs to improve muscular power for the quadriceps muscles. Effectiveness of eccentric exercise in increasing muscle power is substantiated by its role in muscle fiber disruption and ionic membrane permeability changes which in turn act as prerequisite for muscle hypertrophy via  $[Na^+]$  influx and stimulating protein synthesis. The extent of muscle adaptation during exercise training is dependent on the distribution of muscle fiber type within the muscle. Most muscles, such as the quadriceps, are characterized by varying fiber pennation angles and fiber-type composition, depending on the fiber location within the muscle. Variations in morphological and architectural characteristics of the muscle fibers with location indicate that different parts of the quadriceps muscles are differently activated during a specific task. Typically a non-uniform muscle activation produces non-uniform fatigue and recovery within the muscle and as consequence non-uniform muscle adaptation to exercise. After eccentric exercise the extent of muscle fatigue and thus muscle adaptations is greater than following other types of exercise, due to muscle fiber disruption. The fiber injury developed during eccentric exercise also exposes the muscle to pain and intensive weakness, and insufficient muscle recovery following exercise may lead to overuse injury and musculoskeletal disorders. Patellofemoral disorders have a high prevalence among people who are involved in leg eccentric exercise. The underlying mechanisms of the exercise-related patella disorders are not fully understood. It is currently not known whether the injury developed during eccentric exercise preferentially affects particular quadriceps locations and thus leads some regions of the quadriceps to become more fatigable and less active than others.

The multi-channel EMG recording systems used in this study demonstrated a non-uniform change in neural drive within the quadriceps regions during pre- and post eccentric fatiguing contractions, with more pronounced changes for VMO. In the presence of DOMS, muscle activity and fiber CV decreased more for the VMO than for other quadriceps regions. The observation that VMO was more affected may be related to fiber type composition and/or specific architecture of the muscle fibers in this region to stabilize the patella during high intensity leg exercise. The greater muscle hypertrophy of VMO reported by previous studies provides further support to the greater adaptation of this region of the quadriceps to exercise training. These results indicate that VMO is substantially weakened with fatigue and further weakened when DOMS occurs together with fatigue. An insufficient ability of the distal region of the vasti muscles to stabilize the patella as a result of fatigue may expose structures of the knee to abnormal loading during exercise. This may partly

## **Conclusion**

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explain why soreness, weakness, and patellar fatigue fracture are common after intensive fatiguing contractions. This knowledge may be important for trainers and athletes to prevent lateral dislocation of the patella, particularly if their training programs include a large number of heavily loaded eccentric exercises.

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## Resumé

m. quadriceps femoris spiller en vigtig rolle i eksplosive og kraftfulde kontraktioner af benmuskulaturen under sport og dagligdags gøremål. Excentrisk kontraktion er mest brugt under træningsprogrammer, fordi denne kontraktionstype er mere effektiv end koncentrisk kontraktion hvis formålet er at øge muskelkraft. Imidlertid er excentrisk træning af m. quadriceps femoris forbundet med fiberskader og forsinket muscle ømhed (DOMS), hvilket kan reducere quadriceps' evne til at stabilisere knæleddet. Dette kan eksponere knæets strukturer for anormal kraftpåvirkning under træning, hvilket også understøttes af anekdotisk evidens for knæskalsskader efter træning. Det vides ikke om skaden, som udvikles efter excentrisk træning, fortrinsvis påvirker specifikke områder i quadriceps. I dette Ph.D. projekt har det været antaget at fordelingen af muskelfiber størrelser og arkitekturen af m. quadriceps femoris er bestemmende for ikke-uniforme ændringer i aktivitetsniveau og fibres membranegenskaber under udtrættende kontraktioner, samt ikke-uniforme tilpasninger til excentrisk-induceret DOMS. Denne Ph.D. afhandling er delt ind i fem studier. Studie I viste effekten af muskelkraft på reduktionen i muskelfiber ledningshastighed for enkelte motorenheder under udtrættende kontraktioner. Studie II demonstrerede at ændringen i fordelingen af muskelaktivitet under udtrætning og muskeltrætheds genoprettelse er ikke-uniform. Vastus medialis oblique (VMO) udviste en større reduktion i EMG amplitude og middelfrekvens (MPF) under en udtrættende kontraktion og en større forøgelse i MPF under muskeltrætheds genoprettelse. I studie III var excentrisk træning forbundet med reducerede tryksmertetærskler (PPT) og EMG amplitude ved excentriske kontraktioner udført efter 24 og 48 timer. Iblandt quadriceps muskulaturen var VMO den muskel der udviste den største nedgang i PPT og EMG amplitude. I studie IV blev det demonstreret at DOMS undertrykker den typiske genoprettelsestendens af MPF efterfølgende post excentrisk udtrættende kontraktioner. Denne effekt var især udtalt i VMO sammenlignet med andre dele af m. quadriceps. Studie V analyserede muskelledningshastigheden for enkelte motorenheder under udtrættende kontraktioner med DOMS. Effekten af DOMS resulterede i en større reduktion i ledningshastighed under udtrættende kontraktioner end den set i kontrolkonditionen; specielt udtalt for VMO. Afslutningsvis har vi igennem dette Ph.D. projekt demonstreret en ikke-uniform ændring i det neurale drive for regioner af m. quadriceps femoris under udtrætning; dog med mere fremtrædende ændringer for VMO. Muskelaktivitet og ledningshastighed er mere reduceret for VMO end for de andre regioner af quadriceps i tilstedeværelse af DOMS. Disse resultater indikerer at VMO er betydeligt svækket under udtrætning og yderligere svækket når DOMS er nærværende sammen med muskeltræthed. Derfor bør man

være omhyggelig hvis man vil forhindre lateral forskydning af knæskallen, specielt hvis træningsprogrammerne indeholder et større antal belastningstunge excentriske kontraktioner.