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Muscle injury and pain.
**Effects of eccentric exercise, sprint running, forward lunge and sports
massage.**

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"During the finals in 100m at the Olympic games in Berlin 1936, the Swedish sprinter Lennart Strandberg (third place on the picture, finished sixth) sustained a hamstring injury and lost to Jesse Owens. The injury was probably not too severe as he seven weeks later set a new Swedish record running 10.3 seconds in Malmö"

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ABSTRACT

Muscle injuries are the most common injury in sports and both athletes and non-athletes are commonly seen in general practice and in the emergency department. Muscle pain is a common cause for absence from work and the cost to society is high. The present thesis was aimed to study biomechanical and biological causes of muscle injury and pain in order to better design prevention programs and treatment of muscle injury.

Hamstring injuries in sprinters are common, and not caused by external trauma, thus making them a good model for the study of general causes of muscle injury. In study I we compared sprinters with a history of hamstring strain with uninjured runners. Sprinters with a previous hamstring injury were weaker in eccentric contractions, especially at high velocities, compared to uninjured runners. They also showed less flexibility of their hamstrings. One reason for the high recurrence rate of this injury might be that the athletes are not fully rehabilitated after their injury.

In order to make biomechanical studies of fast movements and to compare different muscles we developed the technique of measuring EMG of lower limb muscles during maximal sprint running in study II. The EMG was expressed as percentage of EMG at maximal isometric contraction. This study resulted in normalized EMG graphs for each muscle during sprint running, representing the degree of activity of each muscle. We used this EMG normalization method in study III when performing descriptive biomechanical evaluation of two types of forward lunge (walking forward lunge and jumping forward lunge). Forward lunges are often used by athletes and are thought to be complex eccentric exercises. We managed to simultaneously record the EMG activity with the calculation of muscle length changes by an optic motion analysis system of the hamstrings, rectus femoris and gastrocnemius. Eccentric contractions were found of both rectus femoris and the hamstrings during the first part of the stance phase.

In order to further evaluate these exercises we also performed a study of the acute impact of the exercises on pain and muscle function, as well as after six weeks of training in study IV. Thirty-two football players from one team were included. The forward lunge training was done as an addition to ordinary football training. Whereas walking lunge improved concentric hamstring torque compared to baseline, jumping lunge improved sprint running. Algometer testing showed an increase in pain detection threshold with time in all subjects, including the controls. This is important to consider when using algometers in clinical trials.

Muscle pain often occurs after eccentric exercise, the so called delayed onset muscle soreness (DOMS). Eccentric exercise does not only cause DOMS, it has also been found effective in treating chronic injuries of tendons, and have been suggested as treatment of muscle injury. The pathophysiology behind DOMS is, however, not fully clear. Sensory and autonomic neuropeptides, such as Calcitonin Gene Related Peptide (CGRP) and Neuropeptide Y (NPY) play an important role in pain modulation within the central nervous system. In study V we thus attempted to detect CGRP and NPY *in vivo* in human skeletal muscle at rest and after eccentric exercise. Eight healthy subjects performed strenuous eccentric exercises. Microdialysis of the quadriceps was performed immediately post exercise, after two days and at rest. We were able to detect CGRP but not NPY *in vivo* in human muscle by this technique even though the measured concentrations were low. The detectability of CGRP was significantly increased after exercise, indicating that CGRP after exercise may be involved in the regulation of DOMS. Moreover, CGRP may possibly also be involved in regulating tissue regeneration.

Sports massage has become popular among athletes when treating muscle pain. In study VI we therefore evaluated whether sports massage could prevent DOMS and impaired muscular function following eccentric exercise. Sixteen subjects performed maximal eccentric contractions of the quadriceps in both legs. Massage was given to one leg once daily for three days, whereas the other leg served as a control. The exercise induced soreness and caused reduced strength and function. However, using our evaluation methods we could not verify that sports massage treatment could reduce DOMS or impaired muscle function.

In conclusion, muscle injuries are common among athletes, in particular sprinters, and have a high recurrence rate. The athletes are not always fully rehabilitated before returning to sport. One important factor is decreased eccentric strength. Forward lunge is a complex eccentric exercise that is easy to perform and does not require any equipment. It could be used by athletes, not only to increase strength and speed performance, but it may also be beneficial in the prevention and treatment of thigh muscle injury. Certain neuropeptides such as CGRP can be involved in muscle pain after eccentric exercise. Sports massage is appreciated by athletes but we could not in this study show any benefits regarding pain or recovery.

LIST OF PUBLICATIONS

The thesis is based upon the following papers, which are referred to in the text by their Roman numerals:

- I. **Sven Jönhagen**, Gunnar Nemeth and Ejnar Eriksson. Hamstring injuries in sprinters.
The role of concentric and eccentric hamstring muscle strength and flexibility. American Journal of Sports Medicine 1994 22:(2):262-266
- II. **Sven Jönhagen**, Mats O. Ericson, Gunnar Nemeth and Ejnar Eriksson.
Amplitude and timing of electromyographic activity during sprinting. Scandinavian Journal of Medicine and Science in Sports 1996 6:15-21
- III. **Sven Jönhagen**, Kjartan Halvorsen and Daniel Benoit.
Forward lunge. A biomechanical study of multi-joint exercises of the lower limbs. In manuscript.
- IV. **Sven Jönhagen**, Paul Ackermann and Tönu Saartok.
Forward lunge. A training study of multi-joint exercises of the lower limbs. In manuscript.
- V. **Sven Jönhagen**, Paul Ackermann, Tönu Saartok and Per Renström.
Calcitonin Gene Related Peptide and Neuropeptide Y in skeletal muscle after eccentric exercise, a microdialysis study. In manuscript.
- VI. **Sven Jönhagen**, Paul Ackermann, Tönu Saartok, Tommy Eriksson and Per Renström.
Sports massage after eccentric exercise. American Journal of Sports Medicine 2004 32:(6):1499-1503

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LIST OF ABBREVIATIONS

%MVC	percent of maximal voluntary contraction
°C	degree Celsius
μL	microliter
ACL	anterior cruciate ligament
Ag-AgCl	silver-silver chloride
BSA	bovine serum albumin
CGRP	calcitonin gene related peptide
D	Dalton
DOMS	delayed onset muscle soreness
EMG	electromyography
fmol	femtomol (10^{-15})
h	hour
HPLC	high performance liquid chromatography
Hz	Hertz
JFL	jumping forward lunge
kOhm	kilo-Ohm
min	minutes
mmol	millimol (10^{-3})
MRI	magnetic resonance imaging
msec	millisecond (10^{-3})
N	Newton
Nm	Newtonmeter
NPY	neuropeptide Y
NS	non significant
RMS	root mean square
rpm	rotations per minute
SD	standard deviation
sec	second
VAS	visual analogue scale
WFL	walking forward lunge
Yrs	years

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INTRODUCTION

A well coordinated musculo-skeletal system is essential for successful athletic activity. It is the work of the contracting muscles that moves us forward. The human body consists of more than 300 muscles, constituting 40% of the body mass¹⁰⁰. Skeletal muscle is composed of myofibers, long ribbon shaped cells, surrounded by a lamina. A group of myofibers are bound together by perimysium to form bundles. Different numbers of bundles are enclosed by a strong epimysium, which forms the muscle fascia and continues at the ends of the muscles into tendons attached to the bones. Acute injuries to skeletal muscle, mainly contusions and strains are common and often lead to pain and disability. Unfortunately, muscle injuries are often neglected and misdiagnosed thus leaving the athlete or patient without the optimal treatment.

MUSCLE STRAIN INJURY IN SPORT

Muscle injuries are very common among athletes³⁷ and in sports such as sprint running⁷⁶, football^{5,9,34,93} and American football⁴⁹. The injuries can occur in all muscles, but the most common site of muscle strain injury, especially in high-speed athletes, is the hamstrings.

Hamstring injuries

Dadebo found that hamstring injuries represented 11% of all injuries in Premier league and a third of all muscle strains³⁴. Garrett has shown by computed tomography⁵² that the injuries are primarily localized proximally and laterally in the hamstrings group in the long head of the biceps femoris, but also other parts of the hamstrings group can be affected¹². MRI is a valuable method when distinction between proximal partial and total avulsions should be performed⁶⁸, however most of the injuries can be found in the musculotendinous junction³¹. Ultrasonography is also useful in localizing the injury¹³ and in predicting the severity of the trauma¹²⁶, it can sometimes be superior to MRI¹²⁵. Most partial hamstring injuries heal within 6 weeks³¹, but they have a high tendency to recur^{8,34,37,113}. Complete ruptures from the proximal insertion are often underestimated. They often gives significant functional impairment¹⁰⁷. Surgical repair however, gives good results in acute and sometimes in late cases⁶⁶.

Etiology

The etiology of hamstring muscle injuries in sport has been discussed in the literature. Burkett suggested in the early seventies that imbalance in strength between the antagonist muscles, hamstrings and quadriceps, is one cause of muscle injury²². Studies of football players have revealed increased risk for traumatic injuries, especially ACL-injuries, with a low concentric hamstring/quadriceps ratio¹²⁰. Orchard found that a low preseason concentric hamstring-to-quadriceps muscle peak torque was associated with hamstring injury⁹², but this finding could not be verified in an other study¹⁸. Another important factor for risk to develop hamstring injury in sprinters is tight hamstring muscles⁷¹.

In a one-year prospective study of 180 football players Ekstrand found a correlation between muscle tightness and injuries³⁸. However, in a retrospective study of the same

football players they found no correlation between past injuries and muscle tightness³⁶. Age^{20,50} as well as previous injury¹⁰⁵ have also been found to be risk factors for hamstring strains⁸.

Prevention

Only a few studies have investigated prevention against hamstring injuries. Dadebo found in football players that a standardized stretching protocol could prevent from hamstring injuries³⁴. In a prospective study of eccentric exercise, Askling showed that 10 weeks of eccentric hamstring training on a special dynamic device could prevent hamstring injuries in football players¹¹. Hamstring injuries in sprinters occur without direct trauma, which is often not the case in contact sports such as football or American football. Thus sprinters serve as a good model for the study of these injuries, even though it is easier to perform epidemiological studies on football players.

Treatment

Acute

Traditional acute treatment of muscle injuries includes compression and cold therapy. Thorsson studied a group of athletes that were treated with maximum compression within five min after an acute muscle injury, and compared them to athletes that were treated with rest and elevation only. The compression treatment did not reduce the size of the haematoma or the time to complete subjective recovery compared with no immediate treatment¹²⁶. Maximal compression with an elastic bandage in an experimental setup causes on the other hand immediate cessation of intra muscular blood flow¹²⁴. Accumulated data suggests that cold therapy may reduce the acute pain, but there is no evidence that it improves healing of the injury⁶⁰.

Rehabilitation

Järvinen studied the healing processes of muscle injury and concluded that immediately after the injury, a short period of immobilization is needed to accelerate formation of the scar between the stumps of the ruptured myofibers⁶⁵. However, immobilisation longer than one week is followed by marked muscle atrophy⁶⁴. It is generally believed that rehabilitation of muscle injuries should be directed toward restoration of function, not just relief of symptoms⁵⁶. Sherry performed a study of two different rehabilitation protocols for athletes suffering from acute hamstring injuries. Rehabilitation that included agility and trunk stabilization exercises was more effective than a program emphasizing isolated hamstring stretching and strengthening in return to sports and to prevent injury recurrence¹¹⁵. In another recent study however, intense stretching has been found to be an important part of the rehabilitation⁷⁹ for hamstring injury.

SPRINT RUNNING

Muscle injury is common during sprint running. Sprint running is a natural human movement, however complex. Cavagna described that during the first stance phase of sprint running at high speed, there is an eccentric work done by the muscles of the leg²⁷. During this phase, the muscles elongate while contraction occurs and thus stores mechanical energy in the elastic components of the muscle. The stored energy is immediately released in the concentric phase that follows. This finding is supported by a study of Mann where he used a force plate and film to investigate the kinematics of

sprint running. He found that the greatest effort during the eccentric phase was generated by the hip extensors/knee flexors⁸². There is a difference in ground reaction forces depending on the running technique. Nilsson found that runners with forefoot strikes have less force than rear foot strikers at touch-down⁸⁹.

EMG during sprinting

The activation of different muscles in the lower extremities in sprinting as shown in recordings of temporal distribution of raw EMG activity has been studied by several researchers. In a study of Mann, it was concluded, that increased speed was followed by increased EMG activity in a temporal aspect⁸⁰, however the activity was not graded. Mero used a telemetric device to record activity of elite sprinters during maximal sprinting. The EMG was normalized to maximal integrated EMG during the running stride cycle and the activity was measured ten times during one stride cycle⁸⁴. Nilsson compared walking and running at different velocities, recorded the raw-EMG of some of the muscle groups in the lower leg, and analysed the bursts of EMG⁹⁰ for different muscles, but biceps femoris was not recorded in this study.

ECCENTRIC EXERCISE

Definition

Faulkner has recently clarified the terminology concerning eccentric exercises⁴². An **eccentric contraction** is an activation or contraction of the muscle at the same time as it elongates. The typical example of such a movement is when specific dynamometers are used^{23,111,112}, where the load, the direction of the load and the velocity of the load can be programmed. There is, however, no definition on the degree of activation, or contraction of the contractile elements in the muscle that should be performed. During concentric contraction, the muscle shortens during contraction. An isometric contraction is defined as no changes in the muscle length during contraction..

Eccentric exercise is an exercise, which includes an eccentric contraction of one or more muscles. Eccentric exercise is carried out when a negative work is performed, such as in walking or running downhill⁴¹, often called **eccentric work**. This does not clarify which muscle or muscles that are responsible for the eccentric work. Thus, during an eccentric exercise, all involved muscles do not *per se* undergo an eccentric contraction.

Muscle mechanics

Ito has studied the muscle mechanics in the tibialis anterior muscle complex during an isometric contraction⁶¹. They found by ultrasonography that there is a non-isometric behaviour of the muscle fascicles. During the isometric contraction, the muscle fibres shorten while the tendinous complex elongates. Hof described a similar phenomenon after studies of the triceps surae muscle tendon complex during running⁵⁷. He also found, that during an eccentric contraction where the musculotendinous complex lengthens, the muscle (contractile component) shortens and the tendon (elastic component) elongates.

Open versus closed kinetic chain

The lower limbs are believed to work as an open kinetic chain when using dynamometers where the foot is moving freely¹³⁵. The opposite, a closed kinetic chain, where the foot is anchored to the ground, is considered as more functional¹⁵. This is supported in a study by Augustsson where closed kinetic chain exercise was superior to open kinetic chain exercise in improving jump performance¹⁴. But in the rehabilitation of patients with ACL-injuries a combination of the methods gives better strength gain and therefore is recommended⁸⁵.

An eccentric exercise can easily be performed using equipment for open kinetic chains¹¹. However, it is harder to find functional exercises since those are more complex, especially when two-joint muscles are involved. In complex functional movements such as raising and lowering the body, both quadriceps and hamstrings work together to stabilize the joints at the same time as they perform the movement, a phenomenon described as Lombard's paradox⁷³.

Eccentric exercises in rehabilitation

In clinical practise, Stanish initiated the concept of eccentric exercises in the rehabilitation of patients with tendinopathy¹²¹. Alfredson³ showed that 12 weeks of eccentric calf-muscle training in recreational athletes produced good clinical results in patients with mid-portion Achilles tendinopathy. The same treatment period was used in an other study when treating patients with chronic proximal achillodynia¹¹⁶. In a prospective randomized clinical trial, it was found that 6 weeks of eccentric exercise could reduce pain and improve function in patients with Achilles tendinopathy¹⁰⁶. Shalabi evaluated by MRI the structural healing of patients with Achilles tendinopathy that were treated with eccentric exercise and showed that the treatment resulted in decreased tendon volume and intratendinous signal¹¹⁴. Eccentric exercises have also been used as part of successful non-operative treatment of patellar tendinopathy⁹⁴, as well as chronic lateral epicondylalgia¹²³. Eccentric exercises involve both tendons and muscles.

FORWARD LUNGE

A Norwegian group found that 10 weeks of training with the "Nordic Hamstring" exercise significantly increased the eccentric hamstring strength⁸⁶. Another training method that is widely used by athletes, especially sprint runners and jumpers, is forward lunge, which can be performed while walking or jumping. During the movement the subject lowers and raises the body for each step (figure 2 and 3). Athletic coaches (personal communication) normally think that this is a very strenuous exercise, and it is believed to act eccentrically for both the quadriceps and hamstrings muscles, when breaking the ground forces. Forward lunge is also a closed kinetic chain exercise¹⁰², in contrast to exercises performed in dynamometers. In addition, forward lunges have recently been used as outcome tests after knee ligament surgery^{4,54}. It is therefore interesting to study forward lunges since they may have a potential value as rehabilitation exercises.

MUSCLE PAIN

Muscle pain is a prevalent clinical problem but can be difficult to treat because relatively little is known about the neuronal mechanisms that mediate and modulate muscle pain. Nociceptive nerve endings in muscles and other tissues are equipped with a multitude of receptors for endogenous pain producing and sensitizing agents. The cause of muscle pain is multifactorial and it is found in a wide variety of medical problems³⁰. Muscle pain is generally described as a deep, poorly localized, achy, cramping-like sensation characterizing C-fibre firing, in contrast to the sharp, localized characteristics of cutaneous A-fibre pain. This pain is often poorly localized by patients. Summation of pain is a wind-up phenomenon caused by repetitive pain stimulations, which causes exaggerated pain perception. In a study by Wright assessing the temporal summation of painful stimuli in skin, joint, and muscle, summation was most pronounced in muscle tissue, illustrating the underappreciated role deep tissues play in the development and maintenance of central sensitization¹³⁴.

Delayed onset muscle soreness

It is well known that hard eccentric training, especially in untrained persons, results in marked muscle soreness after one to three days, the so called “delayed onset muscle soreness” (DOMS)^{7,44,47}. DOMS is characterized by tenderness and stiffness during palpation or motion, and the maximum point of tenderness has been suggested to be at the musculotendinous junction^{7,78}. Fridén studied the intramuscular pressure after concentric and eccentric exercise and found that the intramuscular pressure was higher in the eccentric training group together with increased soreness and less ability to sustain tension⁴⁶. There is a cellular response to eccentric exercise which includes breakdown, followed by up-regulation, of the muscle protein desmin, infiltration of inflammatory cells and increased permeability of the cell membrane⁹⁹. The heterogeneity of sarcomere length is also progressively increased after muscle injuries, which has been demonstrated after eccentric exercises in the frog⁹⁵. The changes seen on a cellular level in human muscle are more pronounced two days after exercise than immediately after the exercise, thus indicating the remodelling effect of these exercises¹³⁷.

It has also been shown that intense eccentric exercise may reduce the post-exercise maximal muscular strength by 30%^{23,86}. Since DOMS is easy to perform in an experimental setup it is suitable for studying muscle pain.

Neuropeptides

The cause of pain following eccentric exercise is not yet fully understood. Accumulated data suggests that the peripheral nervous system plays an important role, not only in pain and inflammation, but also in tissue healing and adaptation through the release of neuronal mediators, so called neuropeptides¹.

Both sensory and autonomic neuropeptides have been identified in the musculo-skeletal system, mainly by immunohistochemical studies in animals¹. Only a few studies have focused on human skeletal muscle⁷². Calcitonin gene related peptide (CGRP) is synthesized and released from small, capsaicin-sensitive sensory nerves. This extensive network of sensory nerves, found in virtually all organs, suggests a potential role for

CGRP in diverse physiological and pathophysiological processes.⁴³ The tissue concentration of CGRP, representing the sensory nervous system, has in recent studies been correlated to pain^{26,108} and arthritis¹³⁸. CGRP has, besides nociceptive actions, been demonstrated to act vasodilatory²¹ and to participate in the proliferation of fibroblasts and endothelial cells as well as growth factor synthesis⁵⁸. An adaptive role for CGRP in pain and healing is also suggested in studies of minor orthopaedic trauma, where elevated levels of CGRP have been found in plasma⁹¹. The autonomic neuropeptide Y (NPY) is widely spread in the nervous system and exhibits a wide spectrum of central and peripheral activities¹⁶ and seems to show somewhat opposite effects compared to CGRP, i.e. to act vasoconstrictive⁵⁸ and antinociceptive^{87,88}.

SPORTS MASSAGE TREATMENT

The request for sports massage among competitive athletes has increased during the last years. Among many top-level athletes, this treatment is thought to enhance recovery after training and competitions and to protect from overuse injuries. Specifically, sports massage is believed to reduce the risk for DOMS and to reduce the decrease in muscle strength and function seen after intense exercise⁶. Sports massage is sometimes also used in an attempt to treat minor muscle injuries, and is also given as a prophylactic therapy for these injuries.

There are several types of massage. A sports massage session often includes different kinds of strokes. The effleurage and petrissage techniques that are used in our study are very common when athletes are treated. In sports massage the kneading of the muscles is considered to be harder than in ordinary massage.

The scientific support for the effect of sports massage is limited. Tiidus found no effect of massage on performance and blood flow after eccentric exercise¹²⁷. Similar results were also found in a study of elbow flexors¹³¹. But a few studies using randomisation to massage or not have shown reduced pain in patients with low back pain^{55,132} and less DOMS following eccentric exercise of the elbow muscles¹¹⁸ when using massage.

AIM OF THE STUDIES

The **overall aim** was to study different aspects on muscle injury and pain using a variety of experimental methods. Athletes performing eccentric exercises were used in the models for muscle injury and pain.

The **specific aims** were:

To investigate how common hamstring injuries are among elite sprint runners and if the injuries could be associated with different training methods (Study I).

To study if there are any differences in eccentric and concentric hamstring and quadriceps torques or muscle tightness between sprinters who have suffered from hamstring injuries and uninjured sprinters (Study I).

To make descriptive analyses of the muscle activities in the lower extremity during maximal sprinting using EMG, and thus find a method to compare the activity between different muscles (Study II)

To analyse the length changes in the three major muscle groups of the lower extremities (hamstrings, quadriceps and gastrocnemius) concomitant with the analysis of the activity of the muscles (Study III).

To identify parts of the movements where muscles both elongate and have a high activity, thus defining which muscles act eccentrically during two types of forward lunge, the walking forward lunge and the jumping forward lunge (Study III).

To perform a six-week training study of two types of forward lunge in healthy football players, evaluating the effect on strength, functional and pain parameters (Study IV).

To detect the occurrence of CGRP and NPY in human skeletal muscle *in vivo* at rest and after hard eccentric exercise (Study V).

To examine the potential ability of sports massage in reducing DOMS, functional loss and decrease of muscle strength and to modulate the levels of neuropeptides in the muscle after intense eccentric exercise (Study VI).

MATERIAL AND METHODS

SUBJECTS

In study I, 48 male sprinters from local athletic clubs were sent a questionnaire. The names were obtained from the official ranking from the Swedish Athletic Association. Forty runners replied. Eleven sprinters who had sustained a hamstring injury during one of the two seasons prior to the investigation were included for the experimental study. Nine male sprinters who had never injured their hamstrings were included as a control group. The mean (range) age of the injured sprinters was 22 (18-29) years, and of the uninjured 22 (19-26) years. The mean (range) personal best in the 100 meters was for the injured group 11.01 (10.72-11.39) sec, and for the uninjured group 11.13 (10.81-11.43) sec.

In study II nine sprinters were recruited from local athletic clubs for EMG analysis during maximal sprint running. Their mean (range) age was 25 (18-29) years. None of the subjects had been injured during a period of at least two months prior to the investigation. One subject (subject 4) was excluded from EMG analysis because of technical problems. Another runner sustained a minor injury and was excluded from the second test trials. However, the results from the first test trials of this runner were included in the calculations. Thus, eight runners in the first test trials and seven in the second were subjected to EMG analysis.

In study III five experienced male athletes from local athletic clubs, all skilled in different types of forward lunge, were asked to participate. Their mean (range) age was 31 (27-39) years.

Thirty-two players were included. Four subjects did not perform the last test due to illness or injury unrelated to this study. Thus, 28 subjects performed all the tests and completed the study. The mean (range) age of the subjects was 18 (17-20) years, their average length 178 (166-190) cm, and the mean body weight was 68 (53-82) kg. All subjects gave their informed consent.

In study VI 16 subjects participated, and eight of them were used in study V. They were staff and students recruited from the lab, mean (range) age 29 (20-38) years. They were all used to different levels of physical activity but they were not elite athletes.

QUESTIONNAIRE

48 male sprinters in study I were sent a questionnaire enquiring about their training programs, running career and whether they had sustained any injuries, especially to their hamstring muscles. We asked about the number of training events for different qualities during a normal training week at the four seasons. They also had to state how many years they had trained athletics, and answer about their anthropometric data. Questions about hamstring injury included how it occurred and how it was treated. The data were used for statistical analysis.

FLEXIBILITY TESTING

In study I the tightness of the hamstring muscles was measured with the subject lying supine on a bench with the hip and the contra-lateral leg anchored to the bench by belts.

This method was found by Ekstrand to be reliable³⁹. Anatomical landmarks were indicated on the skin covering the greater trochanter and the fibular head. No warming up was done before this examination. The examiner slowly raised the leg with one hand on the ankle and the other placed over the patella. When the knee began to flex, the angle between the bench and the line connecting the two anatomical landmarks was measured.

MUSCLE STRENGTH TESTING

Muscle strength was evaluated by dynamometers and expressed as torque (Nm).

Kin Com® dynamometer

In study I and VI muscle strength testing was performed on a Kin-Com® muscle dynamometer. Using the Kinetic Communicator Exercise system (Kin-Com, Chattanooga, TN, USA) it is possible to measure eccentric and concentric muscular moments at different angles and velocities. This is a method that is commonly used and has been shown to be highly reproducible⁸³.

Study I

Before muscle torque testing, the subjects went through a standardized warming up schedule consisting of knee squats and stretching exercises of the hamstrings and quadriceps.

The legs and respective muscle groups were measured in random order. The subject sat with a hip angle of 100°. The hip and the leg examined were anchored to the bench by belts to avoid extra movements. During the test the subject held his arms folded over the chest. The motion axis of the Kin-Com was aligned with the bilateral motion axis of the knee joint. The lower leg was placed in the resistance arm, and the angle was calibrated with a plumb line. Correction was made for gravity effect on torque¹³³.

Concentric torques were tested at three different velocities; 30, 180 and 270°/sec, while the eccentric torques were tested at 30, 180 and 230 °/sec. The maximum speed at which tests can be made differs between concentric and eccentric contractions: concentric contractions can be tested at higher angular velocity than eccentric. Before the test at each velocity, the subject acquainted himself with the test by doing two trials, followed by three maximal contractions. If any of the trials was unsuccessful another contraction was allowed. The subject was encouraged verbally and got biofeedback on his performance by following the torque curve displayed on the screen. This has been found to maximize the results⁹⁷. Each concentric contraction was followed by an eccentric contraction. Between the contractions and between the different velocities, the subject rested for around 15 sec and for one minute respectively. Altogether 72 contractions were made between 0° and 90°. The data were processed using the Kin-Com software. The peak torque values, which referred to the maximal torque attained within each contraction mode, were recorded.

Study VI

Kin-Com® dynamometer was also used for strength testing in study VI. Three concentric maximal contractions at a speed of 180 °/sec were tested. Maximal torque between 10 and 90 degrees of knee flexion was noted, and the highest value of these was recorded.

Biodex® dynamometer

The training study of the football players (study IV) was made at another lab (Bosön, The Swedish National Sports Complex) where a Biodex® dynamometer was used¹⁰³. Warming up included 600 m of jogging, mild stretching of the hamstrings and quadriceps and five sub maximal squat jumps. The subjects were thereafter seated on a Biodex® isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA) with a hip angle of 100°. The hip and the non-dominant leg that were to be examined were anchored to the bench by belts to avoid extra movements. The dominant leg was defined as the leg that the player preferred to kick the football with. During the tests, the subjects held their arms folded over the chest. The motion axis of the Biodex® was aligned with the bilateral motion axis of the knee joint. The lower leg was placed in the resistance arm, and the angle was calibrated with a plumb line. Concentric peak torque was tested at 180°/sec. for both the hamstrings and quadriceps muscle groups. During the test, the subject first acquainted himself with the machine by doing a few sub maximal trials, followed by three maximal test contractions. The subjects were encouraged verbally and got feedback on their performance by following the torque curve displayed on the screen. The torque between 10 and 90 degrees of knee flexion was measured, and the highest peak torque value of the three trials was recorded.

ONE-LEG HOP TEST

One-leg hop tests were made in study IV and VI. Each subject made three maximal one-leg horizontal long jumps on the dominant leg¹⁰¹. Ordinary training shoes were used and the ground surface was a plastic floor in study VI and an indoor rubber track in study IV. The subjects were allowed to move their arms freely, but they were not allowed to lift their heels before take-off. The best result was recorded, measured from the toes at push-off to the heels at landing. Pincivero found a correlation between isometric strength testing, especially between the hamstrings strength and one-leg hop test¹⁰⁴.

SPRINT TESTING

Functional testing was also performed in study IV with a 30-meter maximal sprint test. Each subject performed two maximal 30 m sprints, each after an initial acceleration of 30 meter. Electric timing was measured by photocells. The athletes used ordinary training shoes and ran on an indoor rubber track. They rested for about three min between the races. The result of the fastest sprint was recorded. A similar test was made in study II where the runners were instructed to run at maximum speed for 30 m, after 35 m of acceleration. This test situation was known to most of the runners since it is commonly used during training as a test of speed. They were however equipped with EMG-electrodes, cables and telemetric transmitters.

ELECTROMYOGRAPHY

Electromyography was performed in study II and III.

Investigated muscles

In study II seven leg muscles were examined in two trials: In the first lateral hamstrings (biceps femoris), medial hamstrings (semimembranosus / semitendinosus), rectus femoris and gluteus maximus were examined. In the second trial, lateral and medial gastrocnemius, tibialis anterior and lateral hamstrings were tested. In study III we studied the rectus femoris, lateral hamstrings and the lateral gastrocnemius.

Electrodes and preparation

In study II, Ag-AgCl surface electrodes, with a surface area of 9 mm, (D-05-VS, Medicotest a/s, Denmark), were placed with a centre distance of 30 mm and parallel to the muscle fibres on the muscle bulk. The skin was shaved, rubbed with sandpaper and cleaned with acetone. Electrode gel was used and impedance less than 5 kOhm was accepted. In study III pregelled Ag-AgCl surface electrodes were placed with a centre distance of 20 mm, no impedance was measured.

Positioning of electrodes

Table 1 Positioning of surface electrodes, study II.

Muscle:	Location of electrodes:
Lateral hamstrings	15 cm distal to tuber ischiadicum
Medial hamstrings	15 cm distal to tuber ischiadicum
Rectus femoris	27 cm proximal to base of patellae
Gluteus maximus	10 cm distal to spina iliaca posterior superior at the direction of trochanter major
Tibialis anterior	15 cm distal to apex of patellae
Lateral gastrocnemius	10 cm distal to popliteal fossa
Medial gastrocnemius	10 cm distal to popliteal fossa

Table 2 Positioning of surface electrodes, study III:

Muscle:	Location of electrodes:
Lateral hamstrings	50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia.
Rectus femoris	50% on the line from the anterior spina iliaca superior to the superior part of the patella.
Lateral gastrocnemius	at the proximal 1/3 of the line between the head of fibula and the heel.

Normalisation of EMG

The EMG levels were expressed as a percentage of EMG signals recorded during reference, maximum voluntary isometric contraction, (% max EMG)⁴⁰. Subjects were instructed to perform a maximum isometric contraction while EMG was recorded. EMG obtained during the reference maximum contractions was defined as 100%. EMG was also recorded with the muscles fully relaxed in order to define the baseline (0% max EMG). This procedure was done for each muscle investigated.

Table 3 The reference maximum isometric voluntary contractions:

Lateral hamstrings:	Subject prone on a bench. The hip at 0°, and the knee flexed 60°. The lower leg is externally rotated. Subject attempts flexion of the lower leg.
Medial hamstrings:	As above but with the lower leg internally rotated.
Rectus femoris:	Subject sits on a bench with the thigh fixed and the knee flexed 60°. Subject attempts extension of the knee.
Gluteus maximus:	Subject prone on a bench. With the knee flexed 110°, and hip in zero position, subject attempts extension of the hip.
Gastrocnemius:	Subjects stands under a fixed bar with the knee flexed 20 ° and attempts extension of the ankle joint.
Tibialis anterior:	Subject sits on a bench with the thigh fixed. Subject attempts dorsiflexion with the foot supinated and 10° of plantar flexion of the ankle.

Data collection of EMG signals

Study II

Four telemetric preamplifiers (FM Type, IC-600-EMG, Medinik AB, Sweden, signal bandwidth 10-1500 Hz) were used in study II. The signals were transmitted to base stations (FM Type, IC-800-k, Medinik AB, Sweden), where they were amplified and further recorded on an eight-channel FM cassette data recorder (TEAC R-71, TEAC, Japan). The recorded signals were RMS-converted with a time constant of 20 msec (NL-705, Neurolog Digitimer, UK) and then A/D-converted (PC-30 Boston Technologies, USA) and fed to a 386 computer with a math co-processor. Custom-made software was used. A video output card (Digihurst) combined the displayed EMG signal and time pulse signal with the video recording and this was recorded on a VHS videotape. This procedure gives cause to a time delay, which is related to the time constant. The time delay is about 25 msec.

Study III

Electrode cables were used. Muscle activity was measured using Myosystem 2000® (Noraxon Inc. Scotsdale, AZ, USA). The EMG signals were amplified and then sampled at a computer where they were stored for the analysis. The signals were RMS-converted with a time constant of 50 msec and A/D-converted.

BIOMECHANICAL ANALYSIS

Biomechanical analyses were done in study II (sprint-running) and in study III (forward lunge).

Sprint running

In study II EMG was studied during sprint running at maximum speed.

Experimental procedure

The study was done in May, i.e. at the beginning of the competition season for track athletes. Running was done indoors on a rubber track. After the electrodes had been placed, the subjects were allowed to do their ordinary warming up procedure, and then EMG was recorded during resting and maximum voluntary isometric contractions. Subjects made two maximal runs of 30 m at each trial, with a resting period of 10 min in between. The resting period between the two trials was about 20 min. Thus, they made totally four maximal runs.

Collection of data

EMG was stored with a sampling frequency of 50 Hz as compared to the 25 Hz showed on the videotape. The video was used only to find the foot strike and toe off during the stride cycle.

Presentation of data

The first three running cycles after the 35 m of acceleration were identified on the videotape. Each frame had a certain identification number on the screen. This number at the start and end of each running cycle was noted, as well as at foot-strike and push-off. The time numbers of the EMG values (x values) were expressed as percentages of the running cycle. Data are presented as means with one SD. The relative length of different parts of the stride cycle was calculated from the video recording.

Forward lunge

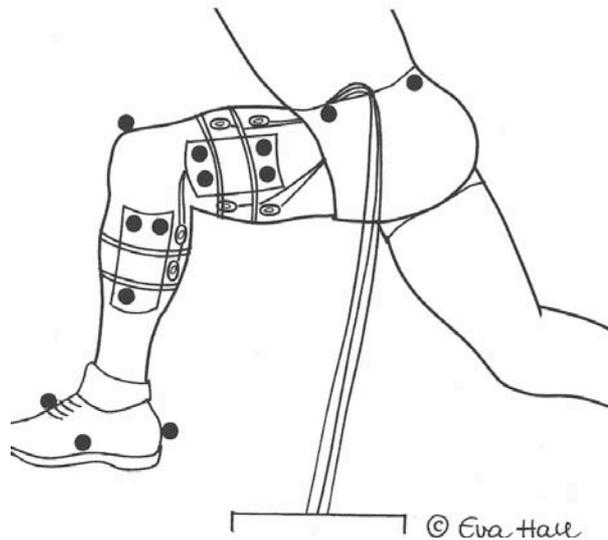


Figure 1 Experimental setup of biomechanical analysis of forward lunge.

In study III EMG and motion analysis were performed in two types of forward lunge.

Experimental protocol

The subjects performed a warming up for 15 min including jogging and mild stretching of the quadriceps, hamstrings and calves, followed by a few forward lunges on the track. Then they were prepared with the equipment for EMG and motion analysis. Thereafter they performed one full cycle of a walking forward lunge (WFL) five times, hitting a force platform with their left leg. The same procedure was repeated for the jumping forward lunge (JFL). The subjects started the WFL standing parallel with the feet, and thereafter began with the right leg. The next step was on the force platform. The subject started the JFL as a sprint start with the right foot in the front.

Motion analysis

Spherical, reflective markers (19 mm) were placed on the pelvis, the left thigh, the left lower leg and the left foot. Four markers were attached on the pelvis with double-sided tape on the anterior and posterior iliac spines. On the thigh and lower leg four and three markers, respectively, were attached to lightweight, padded aluminium plates, which

were taped to the segment. A single marker was placed on the patella. On the foot, markers were anchored to the heel; the midfoot and the distal part of the first metatarsal on the lateral side. The movement of the markers was measured with an eight-camera motion capture system (ProReflex, Qualisys Medical AB, Gothenburg, Sweden). The cameras were placed in a semi-ellipse with the force platform in the centre. The calibrated measurement volume was approximately 5m long, 3m wide and 2m high. The 3D movement of the body segments was then computed from the marker trajectories using the methods of Söderkvist and Wedin¹¹⁹. The exercises were also filmed by a digital video camera, which was placed parallel to the exercise track. The origins of lateral hamstrings, rectus femoris and lateral gastrocnemius muscles were identified by a custom made optical pointing device. The device has two reflective markers with adjustable distance in-between. The device is used to indicate a point in space which lies on the line going through the two markers at a position which is defined by the distance between the two markers²⁵. The end of the device was used to indicate, the estimated location of the origin and insertion of the observed muscles. An experienced orthopaedic surgeon palpated and marked the anatomical positions.

Table 4 Definition of insertion and origin of muscles:

Muscle:	Origin	Insertion
Lateral hamstrings	Pelvis (tuber ischii)	Lower leg (Gerdy's tubercle)
Rectus femoris superior)	Pelvis (spina iliaca of patella)	Lower leg (the upper pole ant
Lateral gastrocnemius	Thigh (post lat fem condyle)	Heel (tubercle of calcaneus)

Analysis of captured data were done with custom MatLab® code. The distance between the origin and insertion of each muscle approximated the muscle lengths. Mean values were calculated for each person and for the whole group.

Force platform

Ground contact was registered with a force platform (AMTI Inc. MA, USA). The analogue data signal corresponding to the vertical component of the force data were split and fed into both data acquisition computers (EMG and motion capture computers). The signal was used to determine the duration of the stance phase and to obtain a common time reference. The force plate data were sampled at 1000Hz and the motion capture data at 100Hz. The sampling was synchronized with 10 samples of force data per frame of kinematic data. EMG data were collected at a separate computer.

Presentation of data

All data was time normalized to 100% of the lunge cycle from foot-strike till toe-off for each lunge movement using 100 data points. The data was then imported into a Microsoft Excel data sheet (Microsoft, Redmond, WA, USA), and the mean value of % EMG and length in cm for each time point was calculated for each lunge cycle.

ECCENTRIC EXERCISES

In study IV and VI maximal eccentric exercises were performed on the Kin-Com® dynamometer with an angle of the hips at about 100 degrees. The subjects were tested

described above (3.4.1.1). Only eccentric contractions were performed and the dynamometer rotated the leg back to the starting position after each contraction, while the subjects relaxed. The subjects were able to follow the exercise procedure on the computer screen and thus get immediate feedback after each contraction. They were also encouraged by the test-leader to perform their best during the session.

Forward lunge

In study III and IV, two types of forward lunge were studied, the walking forward lunge and the jumping forward lunge (fig 2 and 3).

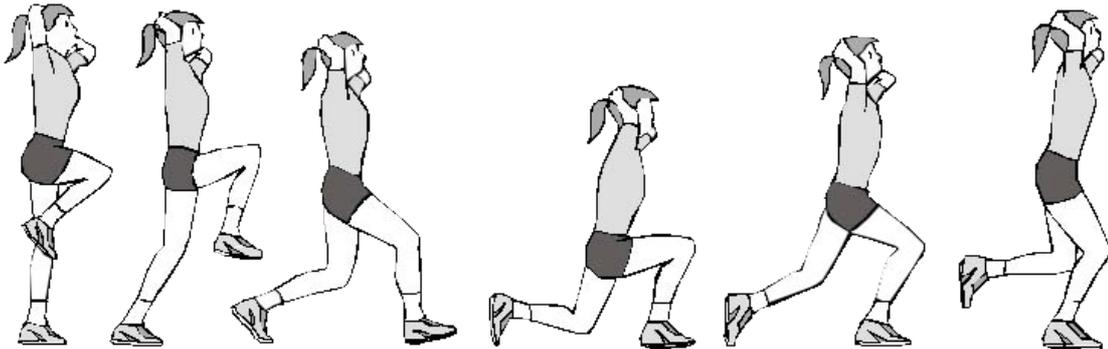


Figure 2 Walking forward lunge.

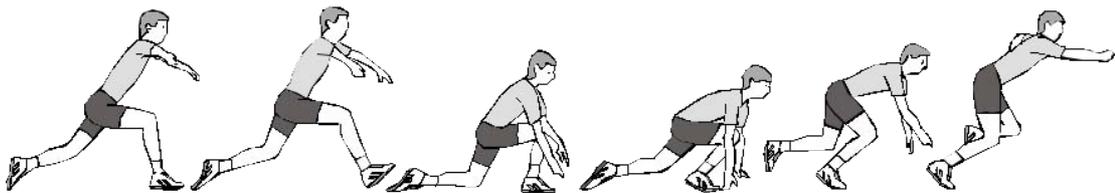


Figure 3 Jumping forward lunge.

EVALUATION OF PAIN

Visual analogue scale

Pain and discomfort of both legs were valuated on a Visual Analogue Scale (VAS) in study IV, V and VI. The test subjects were instructed that, on the scale applied “0” represents no pain or discomfort and 10 the worst pain imaginable. This evaluation was done while walking around in the lab (study V and VI), and after the one-leg hop test (study IV). The VAS scale has been found to be reliable in acute¹⁹ and chronic pain⁷⁵ and the 11 point scale has been recommended³⁵ for pain evaluation.

Algometer pain testing

In study IV a special algometer, A J Tech Commander Algometer™ (Kom Kare Company, Middletown, OH, USA) with a point diameter of 9 mm was used to estimate pressure pain in eight muscle points of the dominant leg, representing either the belly of the muscle or the musculo-tendinous junction. The points were defined in relation to distinct anatomical landmarks and marked with a pen. The test leader pressed the algometer perpendicularly on the marked points, while slowly increasing the pressure. Two values during a single pressure were recorded for each point. The first value was

the pressure of the algometer when the subject starts to feel pain - pain detection threshold. The second value was the pressure of the algometer when the subject could not stand the pain any more - pain tolerance threshold. Due to safety reasons, the maximal pressure of the algometer is 25 N. However, in the majority of the recordings the subjects scored 25 N at the pain tolerance threshold. This value could thus not be used for statistical analysis. We therefore calculated the probability to score 25 at the pain detection threshold. This kind of algometers have earlier been used in studies of muscle pain¹²⁸ and the test results have been shown to be reproducible²⁸.

MEASUREMENT OF NEUROPEPTIDES IN VIVO

Microdialysis

Microdialysis is used as an *in vivo* method, which makes it possible to measure tissue concentrations of different substances in human tissue. In study V and VI microdialysis were performed in order to detect levels of CGRP and NPY. The microdialysis was performed as a surgical procedure under strict conditions. The participants were placed in the supine position on a bench, in light clothes, at room temperature (approximately 22–24°C). The skin was sterilized with a solution of chlorhexidin 2 mg/ml (Klorhexidin 2mg/ml, Pharmacia & Upjohn, Täby, Sweden). Thereafter the skin and underlying subcutaneous tissue, a few mm deep, was anaesthetised with one ml of prilocain, 10 mg/ml (Citanest® Astra Läkemedel, Södertälje, Sweden). The distal part of the vastus lateralis muscle about 10 cm proximal to the knee joint was chosen. A 1.4 mm puncture needle was used to introduce a CMA 60 Microdialysis Catheter (CMA Microdialysis AB, Solna, Sweden) parallel to the muscle fibres. The shaft is made of polyurethane and has a diameter of 0.9 mm and length of 20 mm. The membrane is made of polyamide with a diameter of 0.6 mm and a length of 30 mm, the cut-off is 20.000 D. The catheter was connected to a CMA 107 microdialysis pump (CMA Microdialysis AB, Solna, Sweden) and the infusion speed was selected to 5µL/min. The reason for this relatively high infusion speed is that we suspected low levels of the peptides¹⁰. Isotonic and sterile perfusion fluid was used containing Na 142 mmol/L, K 4.7 mmol/L, Mg 1.2 mmol/L, Ca 2.5 mmol/L, Cl 149 mmol/L, dextranum 40g/L and H₂O (Apoteksbolaget Sweden). The dialysate was collected into a microvial. Equilibration time was chosen to 30 min. We wanted to make analyses as soon as possible after the exercise, but not during the 20 min period where metabolic changes can be found after introduction of the probe¹⁷. Four sampling periods of 30 min each were performed. Every dialysis sample of 150µL was immediately frozen to –70° C. After each microdialysis procedure the catheter was removed and disposed.

Recovery in vitro

A test of relative recovery *in vitro* was performed to analyse how much of a known concentration of CGRP that could be measured by the microdialysis method described above. Recovery was analysed at two perfusion speeds, 1µl/min and 5µl/min.

Radioimmunoassay

For each neuropeptide analysis, the samples from two consecutive 30 min periods were independently run to retrieve two values, from where the average value was calculated. The concentrations of CGRP and NPY were expressed as fmol/mL microdialysate.

CGRP

CGRP was analysed using antiserum CGRP8 raised in a rabbit against BSA conjugated rat CGRP. HPLC purified rat ^{125}I -histidyl CGRP was used as radioligand and rat CGRP as standard. One-hundred μL aliquot's of samples or standards were mixed with 100 μl antiserum solution and incubated for 48 h at 4°C; 100 μl labelled CGRP was added and the solution was incubated for additional 24 h. Free and antibody-bound CGRP were separated using 50 ml Sac-Cel[®] (Anti-Rabbit Solid Phase Second Antibody Coated Cellulose Suspension IDS; Bolton, England). Samples were left for 30 min at room temperature; the reaction was then blocked with 1 ml distilled water. Samples were centrifuged at 3000 rpm for 20 min at 4°C and the supernatants were decanted. Pellets were counted in a gamma counter for 3 min. The detection limit of the assay for rat CGRP was 3.9 fmol/ml. Intra- and interassay coefficients of variation were 8 and 14%, respectively.

Neuropeptide Y

NPY was assessed using rabbit anti-Neuropeptide Y (human, rat) antiserum (Phoenix laboratories, Inc., CA, USA). High performance liquid chromatography (HPLC) purified ^{125}I -porcine NPY was used as radioligand and synthetic porcine NPY was used as standard (SC116, Neosystem, France). One-hundred μL aliquot's of samples or standards were mixed with 500 μl antiserum solution and incubated for 48 h at 4°C; 500 μl labelled NPY was added and the solution was incubated for additional 24 h. Free and antibody-bound NPY were separated using 50 ml Suspension-3[®] (Amersham Biotech, Uppsala, Sweden). Samples were left for 30 min at room temperature; the reaction was then blocked with 1.5 ml distilled H₂O. Samples were centrifuged at 3000 rpm for 20 min at 4°C and the supernatants were decanted. Pellets were counted in a gamma counter for 3 min. The detection limit was 3.9 fmol/ml. Intra- and interassay coefficients of variation were 7 and 12%, respectively.

SPORTS MASSAGE TREATMENT

In study VI the effects of massage treatment on DOMS was evaluated. Within 10 min after hard eccentric exercise on a KinCom[®] dynamometer, all subjects were treated with sports massage. One leg was randomized to massage, and the other leg did not receive any treatment at all. Massage oil ("Dr Schupp", BOFA, Stockholm Sweden) was used. During the therapy the subjects were lying supine on a bench and the entire frontal thigh was massaged. The legs were shaved if needed. The massage started with 4 min of effleurage, which is a light massage and was completed with 8 min of petrissage. Petrissage is a technique where the muscle is kneaded more firmly. Massage was given directly after the exercise and once daily for the following two days.

DATA COLLECTION

Data from study I, IV, V and VI were manually collected and transferred to personal computer or Apple[®] data sheet (Excel[®], Microsoft) for later statistical analysis.

STATISTICS

The angle of the hip joint in the flexibility test in study I was analysed by Student's t test. Peak torque values of concentric and eccentric contractions of quadriceps and hamstrings were evaluated using Student's t test and ANOVA repeated measures design. In study V, we used Friedman ANOVA for non-parametric data to test the change of CGRP at rest and after exercise. In study IV, ANOVA, repeated measures design, including two dependent factors, treatment (treated, non-treated) and time (before, directly after and 3 days after intervention) was used for strength and jump tests. Change over time for strength and the jump tests were tested by MANOVA. Data for VAS were analysed by Friedman ANOVA testing for systematic change over time of pain. Number of days with delayed soreness was analysed by t-test for dependent samples.

In study VI a Linear Mixed model was used to evaluate the differences between the randomized groups with regard to the four continuous outcome variables (hamstring and quadriceps strength, sprint performance and one-leg long jump test). The time effect was also taken into account. Due to variations at baseline the following ratio

$$\text{Ratio} = \frac{T_x - T_0}{\left(\frac{T_x + T_0}{2} \right)}$$

was used in place of the original data values. Due to unequal variances for the time measures, a "Heterogeneous Compound Symmetry" covariance structure was fitted to each model. Different variance components were also estimated for each randomized group. For the ordinal variable of the algometry score, a proportional odds model was setup to evaluate the differences between randomized groups and the time effect. The differences, in pain score, between randomized groups at the time points "after" and "two days" were analysed using the Kruskal-Wallis non-parametric test. All pairwise comparisons were adjusted using either the Bonferroni or Tukey criterion.

In study II and III descriptive biomechanical analyses were performed where no statistical analyses were done.

ETHICS

The Karolinska Institute Ethical Committee at the Karolinska Hospital approved all the studies (88-185, 99-251, 02-359, 03-776).

RESULTS

QUESTIONNAIRE

Forty sprinters out of 48 replied in study I. Of the forty subjects, 30 had sustained hamstring injury with symptoms of sudden pain and associated loss of hamstring muscle power during their running career. Of these, 15 had been injured more than once, and a further six had chronic symptoms of pain and irritation. The injured group had a significantly ($p<0.05$) better personal best result in the 100 meters than the non-injured group. The mean result of the injured group in the 100 meters was 11.05 sec, and for the non-injured group 11.31 sec. There were no differences between the groups in training methods or in the quantity of training.

FLEXIBILITY TESTING

The hamstrings in the uninjured sprinters were less tight. Their range of motion in the hip joint as a group was 74.1° while the range of motion for the injured sprinters was 67.2° ($p<0.05$).

ISOMETRIC TESTING WITH KINCOM® DYNAMOMETER

Concentric

The uninjured sprinters showed significantly higher torques during $30^\circ/\text{sec}$ concentric contractions of the hamstrings ($p<0.05$) and quadriceps ($p<0.05$) compared to the injured sprinters. No significant differences were observed at higher angle velocities (Table 5).

Table 5 Isometric testing of sprinters with or without a history of hamstring injury (torque in Nm, “Qecc 30” refers to eccentric testing of quadriceps at $30^\circ/\text{sec}$, “H”=hamstring, “con”=concentric).

	Injured (n=11)	Uninjured (n=9)	p
Qecc 30	235	300	ns
Qecc 180	277	316	ns
Qecc 230	292	324	ns
Qcon 30	236	291	<0.05
Qcon 180	179	196	ns
Qcon 270	162	175	ns
Hecc 30	127	159	<0.01
Hecc 180	140	175	<0.01
Hecc 230	149	182	<0.001
Hcon 30	127	156	<0.05
Hcon 180	112	121	ns
Hcon 270	113	118	ns

The relation between hamstring and quadriceps torques at high velocities and the torques at $30^\circ/\text{sec}$ was calculated. There was no difference between injured and uninjured sprinters when the quadriceps muscles were analysed. However, the injured

group had relatively higher torques in the contractions of the hamstrings at high angular velocities than the uninjured group ($p < 0.05$).

Eccentric

Measurements of eccentric contraction of the hamstring muscles at 30, 180 and 230°/sec showed a significantly greater ($p < 0.01$, $p < 0.01$, and $p < 0.001$ respectively) peak torque value in the non-injured group than in the injured group (Table 1).

BIOMECHANICAL STUDIES

EMG during sprint running

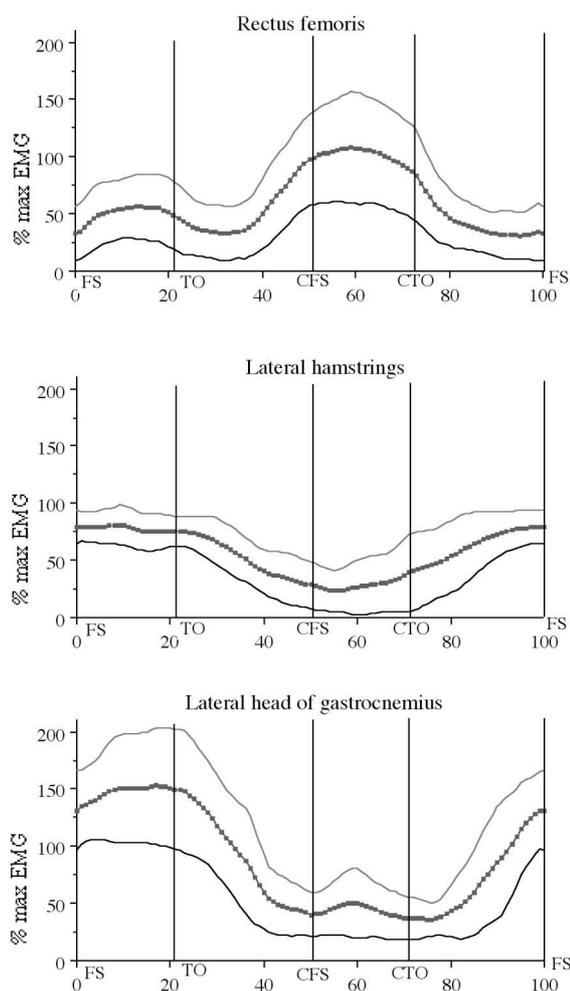


Figure 4 EMG activity during maximal sprint running (FS=footstrike, TO=push-off, CFS=contralateral foot-strike and CTO=contralateral toe-off)

EMG was measured during maximal sprint running in study II. The average time for one full stride cycle was 0.45 sec (SD 0.03 sec). Rectus femoris (fig 4) showed a two-peak EMG activation. The first peak was observed at the middle of the stance phase and the second peak (108% max EMG) occurred during the swing phase. The second

peak of rectus femoris occurred simultaneously to the lowest point of the gluteus maximus and hamstring muscle activation. Lateral (fig 4) and medial hamstrings and gluteus maximus were all active mainly during the end of the second float phase and during the stance phase. The peak of the lateral hamstring occurred at foot-strike (9% of stride cycle). The gluteus maximus had a peak just before foot strike.

Like rectus femoris, tibialis anterior also showed a two-peak activation. The first peak was observed at the beginning of the swing phase and the other peak occurred just before foot-strike. The first peak of tibialis anterior activation occurred simultaneously to the lowest point of the gastrocnemius muscle activation. The activity of lateral (fig 4) and medial gastrocnemius increased successively during the second swing phase and showed high levels just before foot-strike, during foot-strike and at the end of the stance phase.

Biomechanics during forward lunge

Integrated EMG and length change were measured simultaneously in rectus femoris, lateral hamstrings and gastrocnemius in study III.

Hamstrings:

The EMG showed two peaks, one just after foot-strike and one just before push-off.

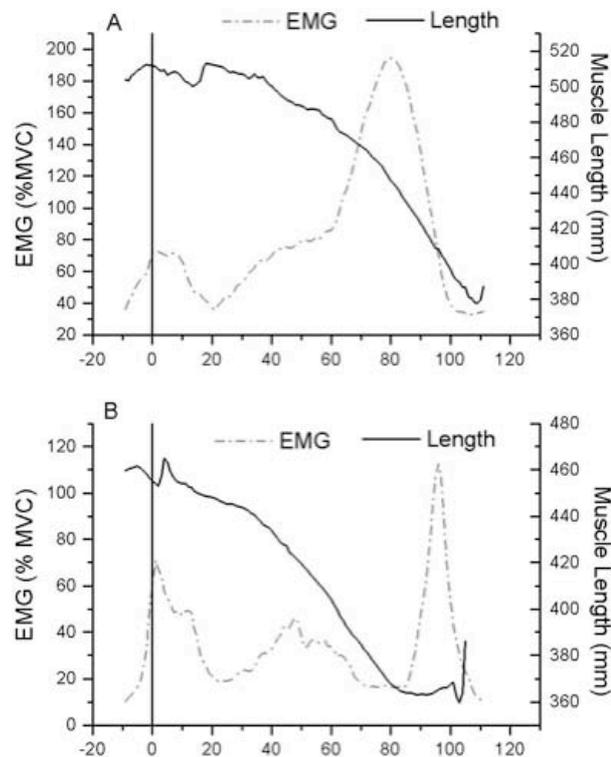


Figure 5 EMG and length as percent of forward lunge of biceps femoris. A=jumping forward lunge, B=walking forward lunge

During the WFL a short period at the beginning of the stance with elongation of the hamstring muscle preceded by high EMG activity was observed. Thus a short period of an eccentric contraction was seen (fig 5). In the JFL, the length of the muscle is almost constant at the first peak, which indicates an isometric contraction, and thereafter there is a marked shortening of the muscle; a concentric contraction. The pronounced second peak during the JFL is due to the fast hip extension in the push-off phase.

Rectus femoris:

During the beginning of the stance phase there is a slight elongation of the rectus femoris preceded by a high activity in EMG. For both the WFL and JFL there is a burst of EMG immediately following foot-strike. In the WFL this is followed by a second burst beginning at 20% stance and peaking at approximately 40% of the stance phase. This coincides with a slight shortening of the muscle followed by a lengthening of the muscle for the remainder of the stance phase.

In the JFL the second burst begins at 20% stance and is prolonged throughout the remainder of the stance phase, with the relatively high activity peaking at approximately 60% stance.

During the first part of the stance in the jumping lunge there is a distinct increase in muscle length, preceded by a peak in muscle activity, thus representing an eccentric contraction. This muscle lengthening is then followed by a gradual concentric contraction followed by an eccentric contraction at the end of the stance phase. Note that this transition from concentric to eccentric contraction occurs with relatively high and constant EMG activity just before push-off.

Gastrocnemius:

For both the WFL and JFL there is an initial small burst of EMG activity at foot strike. This coincides with a rapid decrease in gastrocnemius muscle length. In the JFL this burst is followed by a progressive increase in EMG peaking at approximately 45% stance. The muscle length gradually increases throughout the stance phase and until toe-off.

During the WFL there is also a gradual increase in EMG peaking slightly later at 50% stance. Note that the EMG activity is significantly lower than during the JFL and decreases immediately following this midstance burst before rising again at toe-off. For the WFL there is a period of constant muscle length at 80-100% of the stance phase and relatively low levels of EMG; this corresponds to the transition phase from one leg to the next.

TRAINING STUDY OF FORWARD LUNGE

In study IV 28 subjects completed the training program and the follow up.

Hamstring strength

The WFL group improved the concentric hamstring strength by 35% after six weeks of training, from 92 Nm before the study period to 124 Nm at the end, ($p < 0.001$). WFL also showed a significant increase in strength at day two compared to baseline; the

mean strength at day two was 107 Nm ($p < 0.01$). The JFL group had a mean hamstring strength of 103 Nm at the start and 121 Nm after six weeks, an increase that was not significant because of the spreading within the group. The control group had a hamstring strength of 102 Nm at baseline and 112 Nm (NS) after the six-week period. There were however no significant differences between the training groups over the six-week period.

Quadriceps strength

Immediately after the first training all groups showed a significant decrease in quadriceps strength, even the control group. WFL had a decrease from 171 to 162 Nm ($p < 0.05$), JFL had a decrease from 150 to 132 Nm ($p < 0.001$), and the control group had a decrease from 169 to 157 Nm ($p < 0.05$). At two days JFL and C still had significant decreases in quadriceps strength compared to baseline, with a mean result of 133 Nm ($p < 0.05$) and 156 Nm ($p < 0.001$) respectively, while WFL had a non significant decrease to 186 Nm. The training groups WFL and JFL had no significant improvement in quadriceps concentric strength after the six weeks training period. The control group however, was weaker in the quadriceps after six weeks; the controls performed 169 Nm at the beginning and 158 Nm at the end ($p < 0.01$). No differences were found when comparing the training groups to each other.

Sprint running

Sprint running maximal speed was tested during a 30-meter sprint. WFL increased the performance by 3% (NS) after six weeks of training, while JFL increased the sprint performance by 2% and the control group by 1% (NS). It was only the improvement by JFL as compared to baseline that was significant ($p < 0.001$), but there were no differences between the groups. Immediately after the first exercise, the sprint performance was decreased by 2% in WFL and by 4% in JFL, but only by 1% in controls. The difference between the JFL and controls was significant ($p < 0.01$).

Jumping performance

All three groups improved the jumping performance in the one-leg hop test after six weeks, but there were no differences between the groups. WFL improved their mean performance at six weeks compared to baseline, from 198 to 212 cm ($p < 0.001$), JFL from 191 to 205 cm ($p < 0.01$) and controls from 186 to 198 cm ($p < 0.001$).

Overall pain measured by VAS

Overall muscle pain measured by VAS was analysed during the one-leg jump test. WFL increased their median VAS from 0 to 1 (range 0-6) immediately after the exercise while the median VAS increased from 0 to 3,5 (1-6) in JFL and it remained 0 in controls. The difference between JFL and controls was statistically significant ($p < 0.01$). After two days the VAS for WFL was 1 (0-6) and for JFL 3.5 (0-7). Median VAS for the control group was still 0 (0-5). The number of subjects was too small to show any group differences in VAS between the study groups after two days.

Local pain measured by algometer

Local pain was also evaluated using an algometer. The maximal value that can be recorded is 25 N. We found that the probability to score 25 increased significantly during the testing period. The odds ratio between the first and the fourth test session was 0.3 ($p < 0.001$). There were also significant differences between the muscle points that were tested. Gluteus medius was least tolerable to pressure pain, while the most tolerable point was 5 cm proximal to the patella.

MICRODIALYSIS OF NEUROPEPTIDES IN MUSCLE

In study V, CGRP and NPY were measured at rest and after eccentric exercise in eight subjects using microdialysis. A few microdialysates showed traces of blood by visual inspection of the microvials and those were excluded from the analyses. Overall, the measured concentrations of CGRP and NPY were low, and close to the detection limit.

CGRP

Detectable levels of CGRP in skeletal muscle were found in the majority of the samples. In the control situation at rest, two weeks after exercise, only two out of seven samples (29%) showed detectable levels of CGRP, and in those two samples the concentrations were 4.01 and 4.12 fmol/ml. Directly after exercise, all 15 samples, (one was excluded because of blood contamination), had detectable levels of CGRP (100%). The mean concentration was 4.85 (range 4.13-5.54) fmol/ml. Two days after exercise 12 out of 15 samples (80%) had detectable levels of CGRP, the mean concentration of the 12 samples with detectable levels was 5.4 (range 3.94-6.12) fmol/l. The increase in the number of samples with detectable levels of CGRP after exercise was statistically significant ($p < 0.01$).

The relative recovery of CGRP was for the perfusion speed 1 μ L/min 8,3%, and for the perfusion speed 5 μ L/min 4.4%.

NPY

In all control samples (at rest), NPY was below detection limit. However, after exercise NPY could be detected in some samples. After exercise, a total of 6 out of 30 samples (20%) showed traces of NPY, the mean value of NPY in those samples was 8.2 (4.72-13.98) fmol/ml.

Pain

The median value of pain estimated by VAS, was 0 (range 0-0) at rest, 1 (range 0-5) directly after exercise and 2 (range 1-6) after 48 hours.

MASSAGE TREATMENT

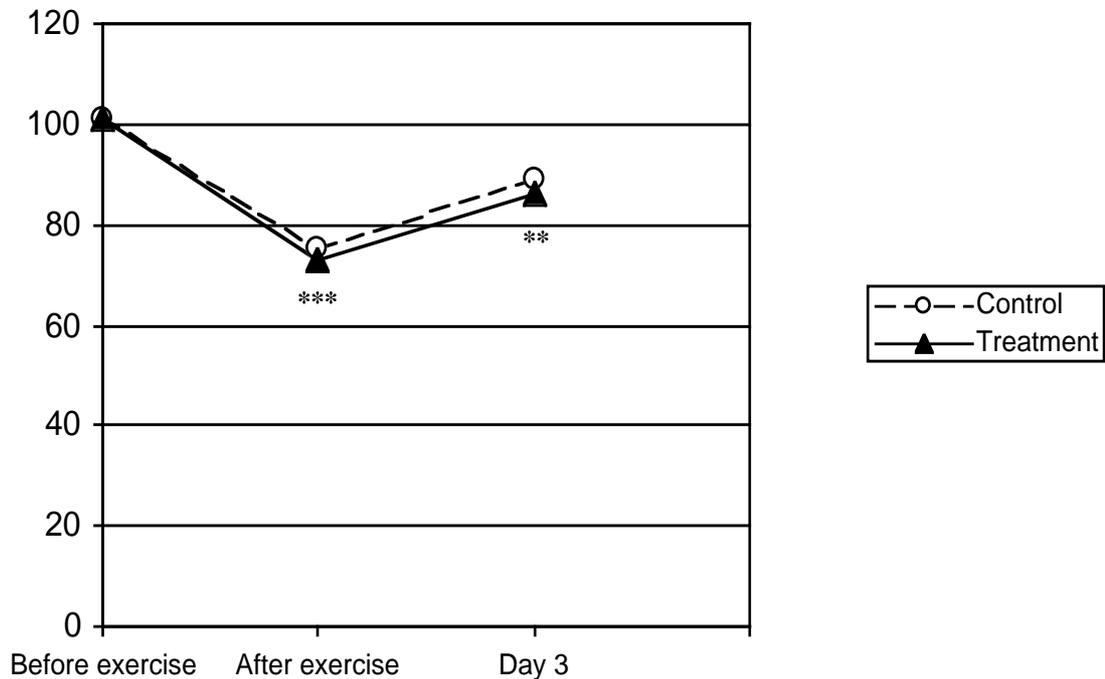


Figure 6 Quadriceps torque (Nm) before, directly after and two days after hard eccentric exercise. “Treatment” leg treated with sports massage, “control” leg is not treated.

In study VI, 16 subjects performed hard eccentric exercise and one leg was then treated directly after, and once daily another two days with sports massage.

Muscle torque

There were no significant differences in maximal concentric strength testing between treated leg and control leg. Mean maximal torque of quadriceps was 101 Nm (range 59-135) preexercise in treated leg and 101 Nm (56-127) in control leg. After exercise and the first treatment session, torque was in the treated leg 75 Nm (47-120) and 73 Nm (44-127) in the control leg. At the third day the torques were 89 Nm (42-125) and 86 Nm (42-127) respectively. The strength was significantly reduced in both groups after exercise ($p < 0.001$), and at the third day ($p < 0.01$), (fig 6).

One-leg hop test

In the functional one-leg hop test, the result patterns were similar to the strength testing (fig 7). There was no significant difference at any time between treated leg and control leg. Before exercise mean values of the long jumps were 160 cm (range 108-195) with the leg that was to be treated, and 158 cm (111-194) with the contra-lateral leg. Directly after exercise and massage treatment the long jumps measured 143 cm (102-190) with the treated leg, and 142 cm (103-181) with the control leg. At the third day the long jumps measured 157 cm (108-189) with the massaged leg, and 154 cm (113-187) with

the control leg. The results were significantly reduced in both groups after exercise ($p < 0.001$), but normalized at the third day.

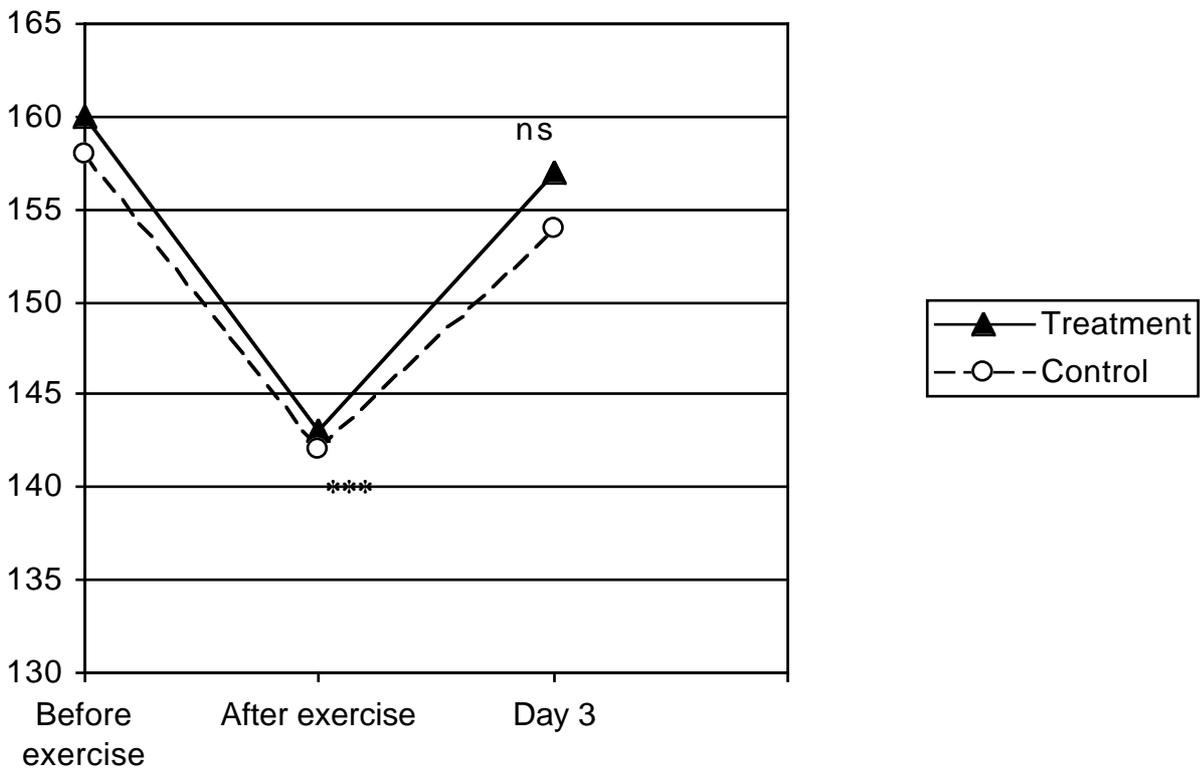


Figure 7 Results (cm) of one-leg hop test before, directly after and two days after hard eccentric exercise. “Treatment” leg treated with sports massage, “control” leg is not treated.

Pain

On the first day directly after the eccentric exercise, the mean value of VAS for the leg to be treated was 2.0 (median 1.5), (range 0-5), and for the control leg 1.9 (1.5), (0-5). After massage treatment the VAS score was 2.2 (2.5), (0-6) for the treated leg and 2.1 (2.5), (0-6) for the control leg. On the third day post-exercise the VAS score was 3.1 (3), (1-6) for the treated leg, and 3.2 (2.5), (1-7), for the control leg. No statistical significant differences between the groups were observed with respect to pain. The subjects reported that the soreness remained for 4.2 days (3-5) in the treated leg, and 4.5 days (3-6) in the control leg (ns).

Neuropeptides

The measured concentrations of CGRP and NPY were very low, a few even below the detection limit. No significant difference between the legs before or after massage treatment was found.

DISCUSSION

HAMSTRING INJURIES IN SPINTERS

Hamstring injuries are a common problem in all high speed sports, especially in top-level athletes. Since the hamstring muscles are crucial for running and sprinting an injury of this muscle group may cause severe functional loss. Better knowledge of the etiology of this injury will help us in preventing and treating this kind of injuries.

Flexibility

In study I it was shown that sprinters that have sustained hamstring injury had tighter hamstrings than the control group. A tight muscle has decreased range of movement (flexibility). This is in accordance with the study of Worrell¹³⁰. Whether the tight hamstrings are caused by the injury *per se* is not clear. Tight hamstrings might be a causative factor for hamstring injuries. One reason why hamstring injuries have a tendency to recur may be that the athlete is not fully rehabilitated with regard to flexibility, when resuming practice, and thus trains or competes with tight hamstrings.

Muscle strength

Our study showed that sprinters with a history of hamstring injuries were significantly weaker in eccentric contractions of the hamstrings at all three velocities. They were also weaker in concentric contractions at low speed. In a study of football players by Paton⁹⁶, there was no correlation between previous hamstring injury and concentric strength of hamstring and quadriceps. In the study of Worrell¹³⁰, concentric and eccentric peak torques were measured for hamstring and quadriceps at 60°/sec and 180°/sec, but no difference between injured and uninjured athletes was found. However, participants in the Worrell study were athletes from different type of sports. Only one participant was a sprinter. Moreover, the average absence from sport due to injury was about two weeks, but in our study the average absence from sport was almost two months reflecting more severe injuries. Hamstring injuries have a tendency to recur^{37,105}. One reason could be that the runner returns to sport before he is fully rehabilitated or that some sprinters for unknown reasons are more vulnerable to hamstring injury than others. Another reason could also be poor eccentric hamstring strength, especially at high angular velocities, since the angular velocities in sprinters are extremely high. After eccentric training there is a rapid adaptation of the muscle, making it more resistant to ultra structural damage and probably also to major injuries. Also, any damage that does occur is repaired at a faster rate^{24,29,110}. This is in accordance with Yu, who recently suggested that there is an adaptive process after eccentric training resulting in new sarcomeres¹³⁷.

Muscle fiber type

Sprinters have a large distribution of fast type II muscle fibers³² and the hamstrings have a higher concentration of fast fibers compared to the quadriceps⁵¹. Fridén has shown that after intensive eccentric training there is a predominant injury of the fast fibers^{45,48,70}.

The tension can become much higher in eccentric contraction, a difference which increases as the contraction velocity increases⁶⁷. Thus, with eccentric contractions it is possible to develop high intrinsic forces within the muscles. Our study indicated that hamstring injury is more common in the faster sprinters than in the less fast athletes. It may be possible that sprinters with high concentrations of fast type-II muscle fibers have an increased risk of developing muscle injury if the eccentric function is poor. The relation between the moment of concentric contraction at slow and fast angular velocities may reflect the quantitative distribution of fast type-II muscle fibers⁶⁹. We found in our study that the sprinters from the injured group performed higher torques in concentric contractions of the hamstrings at fast speed in relation to slow speed compared to uninjured sprinters. This may thus be due to a higher percentage of fast type-II muscle fibers in the injured runners. Thus, the faster the runner the more important is the eccentric training of the hamstrings.

BIOMECHANICS

Sprint running

Running speed is an important factor for success in athletics. Speed performance depends largely on the ability to coordinate muscle actions. Electromyography (EMG) is a useful tool in evaluating the activation from different muscles during movements. A sprinter though can attain speeds for a few seconds that are two to three times greater than those they can maintain for several hours. The high running speed however, makes it technically difficult to perform EMG-measurements.

In study II, EMG was measured during maximal sprint running. The lowest values of EMG varied between different muscles with mean values of 18% in gluteus maximus and 48% in the gastrocnemius. This is probably due to pretension in the muscles.

However, we did find an interindividual variability, some runners seemed to be more relaxed during running and thus had lower values.

One might expect that the equipment they wore, i.e. surface electrodes, cables and telemetric transmitters, would have negatively affected the runners. However, this was not observed, on the contrary the runners achieved results in the 30-meter tests which were better than, or just above, their personal best on this specific test.

In our study the lateral and medial gastrocnemius showed high and even activity throughout the support phase including push-off, which contradicts the findings of Mann^{80,81} as well as those of Simonsen¹¹⁷, where no activity was observed just before and during push-off. Mann concluded that little or no push-off occurs from the posterior calf muscles. However, the high activity of the gastrocnemius muscles shown in our study indicates that involvement of a push-off phase cannot be excluded. Mero⁸⁴ showed that the activity of the gastrocnemius muscles is high throughout the support phase, and concluded that this muscle plays a primary role in the push-off of sprinting, thus supporting our findings.

The medial and lateral hamstrings and the gluteus maximus all have their peak activities in the same phases of the running cycle. The activity of the lateral hamstrings

is somewhat lower than that of the medial hamstrings. They are active mainly during the end of the second float phase, where they act eccentrically to avoid flexion on the hip and extension of the knee, and at the beginning of the stance phase. The peak activity of the rectus femoris occurs at the swing phase when the hamstrings and the gluteus maximus show their lowest activity levels. During this period they work as antagonists. However, the second peak of rectus femoris, which is the lower peak, occurs during the peak of gluteus maximus and the hamstrings. This occurs during the support phase.

The observed co-contractions might be a muscular strategy to stabilize the joints. Two counteracting muscular moments will produce a net zero moment about a joint.

However, the exerted muscular force will together create a compression force, adding stability to the joint.

Another effect of co-contraction might be to create a "pretension situation" in the muscle and tendon. In this way the muscle will be more prepared in counteracting motions through an eccentric contraction.

The curves of gluteus maximus and gastrocnemius respectively are quite similar in our study as in a study of Jacobs⁶². We showed that the highest activity of medial hamstrings is found at foot strike while in the Jacobs study the activity is quite low at foot strike. The different velocities used could possibly explain this difference. In our study the runners have a velocity of 10 m/sec comparing to the velocity in the Jacobs study of 6 m/sec. Thus, with higher speed in sprinting there is a higher activity in the hamstrings at foot strike.

Forward lunge

Forward lunge is a training method that has commonly been used by top-level athletes such as sprinters and jumpers. Many coaches have implemented the ideas of eccentric training, and forward lunge has been believed to be valuable for eccentric training of quadriceps and hamstrings. It is easy to perform and no equipment is needed. There is however no study that has shown whether this is an eccentric exercise or not.

In study III, we used EMG to analyse in which period of the movement during walking and JFL different muscles were active. The EMG activity is normally followed by a muscle contraction after about 50 msec¹¹⁷, the so called electromechanical delay. We also wanted to study if the muscles shorten or elongate during different periods of the movement using a reflexive motion analysis system. In the analysis, the origin and insertion of the muscles are assumed to be points and the muscle lengths are approximated as the linear distance between the origin and insertion. In reality, the paths of the muscles are curvilinear, and the contraction along the path of the muscle may not be uniform. This is nevertheless a useful approximation, which has been used previously⁵³ to calculate muscle lengths from the angles of the involved joints.

Hamstrings

We found that the hamstring muscles only had a short period of elongation during the first part of the WFL. In the first part of the JFL the hamstrings did not change the

length at all, indicating an isometric contraction. The length of the hamstrings depends on the angle of the knee and the hip since they are two joint muscle. The angle of the hip has more impact on the length of the hamstrings than the angle of the knee⁵³. Small changes in the hip angle may compensate for changes in knee joint angle, which may explain why there is an isometric contraction of the hamstrings even though the knee flexes during the first part of the stance phase.

Ito has found⁶¹ that during an isometric contraction muscle fibres shorten while the tendinous complex elongates. Moreover, Hof found⁵⁷ that during an eccentric contraction where the musculotendinous complex lengthens, the muscle shortens and the tendon elongates. In the forward lunge where we have found an isometric contraction with a high EMG activity of the hamstrings, there may be a contraction and shortening of the contractile component while the elastic components stretches and thus stores energy for recoiling in the latter part of the gait⁶³.

Rectus femoris

In the rectus, we observed two sections of the WFL where the muscle elongates during EMG activity, namely at the foot strike and at the end of the movement. The biomechanics are somewhat different in the jumping lunge; in the beginning of the foot strike, there is a marked elongation of the quadriceps. During the first period of this elongation the EMG activity is high probably because of the breaking of ground forces.

Gastrocnemius

The gastrocnemius muscle acts similarly in both types of lunges. There is a prolonged elongation throughout the stance phase. The EMG shows two peaks, one in the middle of the stance phase and one at the end. The peak of EMG in the middle of the stance may represent an eccentric contraction where the contractile components contract and the elastic components elongates in preparation for the concentric contraction in the push off that follows.

Based on our descriptive analysis we found that the quadriceps work eccentrically during the first part of a forward lunge, especially the jumping forward lunge. The hamstrings have an isometric contraction during the initial period of the stance phase, and the gastrocnemius works eccentrically during most of the stance phase. Thus eccentric, concentric and isometric contractions are found during the forward lunge. Contrary to popular belief in the track and field community it is not an exercise that elicits prolonged hamstring eccentric activity.

TRAINING STUDY OF FORWARD LUNGE

The athletic community can help us in our search for new rehabilitation models. In study III we showed that forward lunge could be used as an eccentric exercise for the quadriceps and the hamstrings. We therefore wanted to study the acute effects on performance and pain parameters as well as the effects on performance after six weeks of training with forward lunge.

In study IV, twenty-eight junior football players thus underwent a six-week training study of two types of forward lunge. The players were randomized to a walking forward lunge group (WFL), a jumping forward lunge (JFL) group and controls. No differences could be found between the study groups. This can be explained by the power, the number of subjects was too small to detect differences, or that the intervention was done during a too short period. We choose to study players from only one team to ensure that they had similar training schedules, we could thus not use more

players to gain a better power. Compared to baseline in the groups, WFL improved the hamstring strength while JFL improved the performance of sprint running after six weeks.

Immediately after exercise the jumping lunge group exhibited decreased hamstring concentric strength as compared to baseline. This tendency was supported by the significantly decreased sprint performance in the jumping lunge group, compared to the control group just after exercise, indicating that the work performed by the hamstring muscles during the jumping lunge was strenuous.

All three groups, including the control group, demonstrated a significant decrease in quadriceps strength immediately after training. This is probably caused by exhaustion from the testing procedure itself. In this study, no eccentric strength testing on the Biodex® was performed. We did not want the testing procedure itself to produce extra eccentric training since it is known that one bout of eccentric exercise has major impact on muscle adaptation³³. We believe that the sprint test represents a good test of eccentric muscle function¹¹ and we thus included this functional testing^{15,104}.

After two days, the VAS for WFL and JFL was 1 and 3.5 respectively, while VAS for the control group was 0. Many of the players that had performed forward lunge complained of soreness at day two. The number of subjects, however, was too small to show any statistically significant differences between the groups.

About half of the subjects from WFL and JFL scored very high (VAS=5-7) after two days, and thus seemed to experience a distinct DOMS, while the other half scored very low (VAS=0-2). It could be speculated that different training experiences explain this phenomenon, those that did not have any DOMS may have been used to similar exercises earlier.

We found that these young football players were able to tolerate pressure pain from the algometer very well. Interestingly, the probability to score 25 N increased significantly during the testing period. Thus it seems as if the subjects were able to tolerate pain better with time and/or were more familiar with the testing situation. This contradicts in some aspects the above reported good reproducibility of the algometer²⁸. Earlier studies¹³⁶ though, have shown similar phenomenon when measuring pain thresholds with heat. However, as far as we know, this phenomenon has not been reported earlier in connection with the use of algometers. This finding is important to consider if the algometer will be used to evaluate treatment for pain in clinical trials.

After six weeks of training, the walking lunge group increased 35% in concentric strength of the hamstrings, an increase that is surprisingly high. In the study of the Nordic Hamstring exercise⁸⁶, the football players of that study increased their isometric hamstring strength by 7% and the eccentric strength by 11% after a 10 week training period. This difference may be explained by the age and level of the players, we used junior players and in the Norwegian study the participants were probably older than ours and maybe more trained.

All three groups had a significant improvement in the one-leg hop test. Probably because they were not used to this test and they learnt the technique during the testing period.

Neither of the groups increased their quadriceps strength significantly, instead the control group had a significant decrease (-7%) of their quadriceps strength. This is difficult to explain since one would think that these adolescent athletes would increase their muscle strength by their ordinary football training. The players that trained the JFL had a small but significant increase in sprint performance after the six-week

training period. The exercise also resulted in a significant acute soreness and decrease in sprint performance directly after the first training session, compared to controls. Thus, the JFL training method has a significant impact on sprint performance. It could be speculated that this is due to a higher degree of eccentric work in the JFL, and this in turn enhances the turnover of new sarcomeres.

MUSCLE PAIN AFTER ECCENTRIC EXERCISE

The pathophysiology behind the DOMS after intense eccentric exercise is not yet fully understood. The muscle pain that occurs has a peak after 24-72 hours⁴⁸ and may be prolonged up to a week, this findings are confirmed in our study (V, VI). This pain however is mainly occurring in untrained persons or athletes performing unusual exercises and there is a rapid adaptation to eccentric exercises²⁹.

Neuropeptides

Neuropeptides such as CGRP and NPY have gained increased interest in pain studies during the recent years. These peptides are mainly found within the central nervous system, but could also be found in the peripheral musculo-skeletal system^{1,59,72}. We were therefore interested in developing a method to measure CGRP and NPY *in vivo* in human muscle and to study the response after eccentric exercise, and if these substances may be involved in the pain process during DOMS. In study V, we demonstrated that detectable levels of CGRP could be analysed in human skeletal muscle using the microdialysis technique. Moreover, the increased detectability of CGRP observed after hard eccentric exercise was parallel to increased experience of pain. This supports earlier studies suggesting that CGRP is involved in the pain modulation during DOMS. It could also be speculated that CGRP is involved in the rapid formation of new sarcomeres found by Yu¹³⁷.

Only a few samples gave detectable levels of NPY after exercise. The inconsistency in NPY detection could be due to the low microdialysis membrane cut-off (20.000 D). The molecular weight of NPY is 4272 D¹²², while the molecular weight of CGRP is somewhat lower, 3789 D⁴³. This might be a reason why less NPY than CGRP could be found in the dialysate. However, one study using the same membrane cut-off as in our study, was able to detect CGRP in human skin¹⁰⁹.

In our experimental model muscle pain was induced by eccentric exercise, which is a well documented model⁷⁷ that is easy to perform and standardize. The subject's experience of pain, as measured by VAS, was increased two days post exercise, which is consistent with earlier reports^{44,47}. The increased pain level, described as DOMS, was related to the finding of increased detectability of CGRP.

In fact, one recent study demonstrates increased levels of CGRP in the motor neurons of medial gastrocnemius muscles in the rat 72 hours after eccentric downhill running⁵⁹. Other studies on minor orthopaedic trauma, such as sprains and muscle injuries, show elevated levels of CGRP in plasma⁹¹. After tendon rupture in the rat, there is extensive nerve ingrowth into the tendon, which is normally devoid of nerves, expressing CGRP². Thus, these studies indicate that the peripheral nervous system initially reacts upon exercise and injury, by release of regulatory neuronal mediators, such as CGRP.

CGRP has been suggested to exert trophic effects, i.e. proliferation of fibroblasts and endothelial cells in response to stress. Our detection of CGRP after eccentric exercise may therefore be assumed to reflect tissue recovery by stimulating tissue regeneration. CGRP is also implicated in nociception. In our study we observed increased levels of CGRP after eccentric exercise together with increased experience of pain. Thus, CGRP may be involved in the pain regulation of DOMS after heavy exercise while simultaneously stimulation of tissue proliferation.

SPORTS MASSAGE

We have noticed an increased demand for sports massage among our top athletes. The athletes use massage for recovery after hard training but also as a preparation for important competitions⁶. After massage the athletes often experience a general relaxation and the muscles feel softer. We therefore wanted to study if sports massage could reduce the effects of DOMS (study VI). But we could not with our methods confirm any local effects on reducing delayed muscle soreness (DOMS), functional loss or decrease of muscle strength.

In this study both maximal strength tests and functional tests were used to evaluate the effect of massage post-exercise. A significant reduction in maximal muscle strength was found directly after the exercise. After two days there was also a distinct reduction of maximal strength. However, treatment with sports massage did not affect this strength reduction.

One-leg hop test is dependent on muscle strength as well as coordination. Thus it may be a test also of the recovery of the neuro-muscular system involved. As was the case with the muscle strength, the one-leg hop test showed a significant reduction of strength after heavy eccentric exercise. Again, massage treatment did not alter this loss of performance. This study was done in an experimental setting, which probably differs from real life settings where athletes might experience DOMS from certain competitive situations such as cross-country running with strenuous downhill running, or after e.g. an exhausting volleyball match with a lot of jumping.

Our results showing no effects on the muscular performance by sports massage is also confirmed by other studies. Tiidus and coworkers studied the effect of sports massage on muscular strength and blood flow after eccentric exercise of the quadriceps¹²⁷. In their study the quadriceps was treated by massage once daily during four days post exercise, and the contra-lateral leg served as control. Immediate post-exercise maximal strength measures had declined to approximately 60-70% of the pre-exercise values in both legs. They found no significant differences in maximal strength measures between massage and control legs up to 96 hours post-exercise. They also found that massage did not significantly elevate arterial or venous mean blood velocity above resting levels. In a study of Weber and coworkers¹³¹, subjects were randomised to sports massage or not after eccentric exercise of elbow flexors, and there was no effect of massage on pain or strength reported.

This study showed no differences in pain, as scored on VAS scale, between the massaged leg and the contra-lateral control leg. Moreover, the treatment did not shorten the duration of soreness in the leg.

In an attempt to measure markers of pain^{98,129,138} and vasoregulation²¹ the presence of the sensory CGRP and autonomic NPY was studied by microdialysis and radioimmunoassay. The levels were low and in several cases undetectable and changes

were thus difficult to detect. However, we did not find any difference in the presence of CGRP and NPY, between the treated and the contra-lateral control legs.

This may not preclude, however, that sports massage may have central effects, which cannot be detected in the study design that we used. In fact, a few studies using randomisation to massage or not have shown reduced pain for patients with low back pain^{55,132} and less DOMS following eccentric exercise of the elbow muscles¹¹⁸ when using massage. This antinociceptive effect might be explained by the release of oxytocin⁷⁴. Relaxation of the muscles that athletes report after sports massage has not been evaluated in this study.

FINAL COMMENTS

Our findings taken together with accumulated data from earlier studies, imply that eccentric strength training is important for the prevention and treatment of muscle injuries, especially in high speed sports such as sprint running and football. The walking and jumping forward lunge may be used as training methods to improve performance in many sports such as sprint running but they may also be tried as therapeutic tools in the prevention and treatment of thigh muscle injuries.

Future perspectives

Studies of the prophylactic effect of forward lunges upon muscle injury as well as the prevention of overuse injuries are of great scientific and clinical interest. Other specific athletic training methods could also be used in research, and biomechanical as well as biological parameters in specific exercises should be further analyzed. The training effects of different exercises need to be systematically evaluated before intervention studies can be performed. EMG could be combined with motion analysis systems to study different natural sport activities in order to identify movements with a high risk of injury.

Neuropeptides could be further studied in relation to DOMS, muscle pain and muscle regeneration to increase our understanding of the underlying biochemical mechanisms. The preventive effect of sports massage on muscle injury in athletes and on muscle pain in work related musculo-tendinous pain syndromes is also of interest for future studies.

CONCLUSIONS

Hamstring muscle injuries are common among sprint runners, and are probably related to the number of fast type II fibres. Fast runners are more prone to injury than slower. We found no association between different training methods and muscle injury (Study I).

Eccentric exercises and flexibility training of the hamstrings are important in the rehabilitation since runners with a history of hamstring injury have decreased muscle strength and flexibility (Study I).

It is possible to perform integrated EMG measuring during maximal sprint running and thus compare different muscles of the lower leg. Rectus femoris has the highest activity during the swing phase in sprint running. Gluteus maximus and medial and lateral hamstrings show a peak activity before and during foot strike, where they work eccentrically. During the support phase rectus femoris, gluteus maximus and the hamstrings co-contract. Gastrocnemius has the highest activity just before push-off (Study II).

It is possible to perform measurements of length changes simultaneously with the activity of multi joint muscles during movements using EMG and optical motion analysis system. This makes it possible to analyse in what range a movement is eccentric, concentric or isometric (Study III).

The quadriceps works eccentrically during the first part of a forward lunge, especially during the jumping lunge. The hamstrings perform an isometric contraction during the stance phase, and the gastrocnemius works eccentrically during a part of the stance phase (Study III).

A six-week period of training with walking lunge improved the hamstring concentric strength, while training with the jumping lunge improved the performance of sprint running.

Algometer testing itself increased the possibility to adapt to and thereby tolerate pressure pain. This is important to consider when using algometers in clinical trials (Study IV).

It is possible to perform measurements of CGRP in the human muscle using microdialysis, however, the relative recovery is small. CGRP is increased in the human muscle after hard eccentric exercise, and may be related to the pain caused by this exercise. (Study V).

We could not find any effect on the local recovery after hard eccentric exercise using sports massage of the quadriceps muscle. We could also not find any effect on the pain and soreness that normally follows this kind of exercises shown (Study VI).

POPULÄRVETENSKAPLIG SAMMANFATTNING

Muskelskador är mycket vanliga inom idrott. Det är till exempel den vanligaste fotbollsskadan. De är i regel godartade men kan ge långvariga funktionella besvär. Smärttillstånd från muskulaturen är ett problem som förekommer dels inom idrotten men även inom arbetslivet.

Flera studier har de senaste åren påvisat god effekt av excentrisk träning vid smärtor i senor. Vid excentrisk aktivitet utför man ett bromsande muskelarbete, såsom vid gång nerför en backe, muskeln förlängs samtidigt som den aktiveras. Detta kan ge upphov till kraftig träningsvärk hos otränade individer. Excentrisk träning kan emellertid ge ett snabbt träningsresultat.

I vår första studie undersöktes sprinterlöpare som tidigare ådragit sig muskelbristningar i hamstringsmuskulaturen på lårets baksida, men som ansåg sig återhämtade från den skadan. Dessa löpare hade sämre excentrisk muskelstyrka i hamstrings jämfört med tidigare oskadade löpare. De hade även tecken på en högre andel snabba muskelfibrer och var dessutom stelare i sin muskulatur.

I en biomekanisk studie vidareutvecklades metoder för att mäta musklernas elektriska aktivitet med hjälp av elektromyografi (EMG) vid maximal sprinterlöpning. Löparna hade ytelektroder över musklerna och signaler sändes via telemetri till en mottagare. Vi kunde för de stora musklerna på benen illustrera aktiviteten under hela löpcykeln. Denna metod använde vi senare då vi undersökte idrottare som utförde olika typer av utfallssteg. Utfallssteg karaktäriseras av ett bromsande moment och är vanligt inom idrotten. Den är dock komplex med muskelgrupper som går över flera leder involverade. Vi använde EMG för att mäta var i rörelsemönstret som muskelaktiviteten var hög, samtidigt som vi med ett optiskt tredimensionellt rörelseanalyssystem undersökte de olika musklernas längdförändring. Direkt efter fotisättning förekom excentrisk muskelaktivitet framför allt på framsidan av låret men även i hamstrings på lårets baksida.

Vi genomförde därefter en träningsstudie med 32 fotbollsspelare som lottades till en av tre grupper. Den första gruppen tränade ”gående” utfallssteg två gånger i veckan i sex veckor förutom den vanliga träningen. Den andra gruppen tränade ”hoppande” utfallssteg och de i den tredje gruppen tränade enbart sin ordinarie träning. De som tränade ”gående” utfallssteg fick en klar förbättring av styrkan i hamstringsmuskulaturen jämfört med utgångsvärdet. De som tränade ”hoppande” utfallssteg uppvisade en liten förbättring av sprintsnabbheten jämfört med utgångsvärdet.

Mekanismerna vid träningsvärk är ännu ej helt kartlagda. Signalsubstansen CGRP är involverade i smärtmekanismerna i det centrala nervsystemet. Vi undersökte därför om några sådana substanser kunde vara involverade i smärtan vid träningsvärk. Med hjälp av en mikrodialys slang som fördes in i muskulaturen på lårets framsida togs vävnadsvätska från muskulaturen efter excentrisk träning. Efter träning fann vi ökade halter CGRP i musklerna. Det kan diskuteras om inte denna signalsubstans är involverad i träningsvärken, och även i den uppbyggnad av muskulaturen man får. Idrottsmassage är en populär behandlingsmetod hos idrottare och ges ofta i avslappande syfte. Tidigare forskning har visat att idrottsmassage kan ge en generellt smärtdämpande effekt. I en studie tränade försökspersoner ett hårt pass med excentriska övningar, därefter masserades det ena benet en gång dagligen i tre dagar. Träningsvärk

uppstod och försökspersonerna hade försämrade värden i styrke- och hopptester efteråt. Ingen skillnad förelåg dock mellan det ben som hade masserats och det andra benet. Med våra metoder kunde vi alltså inte påvisa att idrottsmassage förbättrade återhämtningen i benen efter hård träning.

Sammanfattningsvis visar våra studier tillsammans med data från tidigare studier, att sprinterlöpare som drabbats av muskelbristningar har en nedsatt excentrisk styrka och rörlighet i hamstrings. Detta kan sannolikt till viss del förklara varför dessa skador ofta upprepas. ”Gående” och ”hoppande” utfallssteg kan användas inte bara för att förbättra muskelstyrka och sprints snabbhet hos idrottare, utan torde även kunna prövas i förebyggande syfte och som behandling vid muskelskador. Indikationer finns på att CGRP kan vara involverad vid träningsvärk och muskeluppbyggnaden efter excentrisk träning. Vi kunde inte med idrottsmassage påverka smärta och nedsatt prestationsförmåga efter excentrisk träning.

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REFERENCES

- 1 Ackermann PW, Finn A, Ahmed M. Sensory neuropeptidergic pattern in tendon, ligament and joint capsule. A study in the rat. *Neuroreport* 1999;10:2055-60.
- 2 Ackermann PW, Li J, Lundeberg T, Kreicbergs A. Neuronal plasticity in relation to nociception and healing of rat achilles tendon. *J Orthop Res* 2003;21:432-41.
- 3 Alfredson H, Pietila T, Jonsson P, Lorentzon R. Heavy-load eccentric calf muscle training for the treatment of chronic Achilles tendinosis. *Am J Sports Med* 1998;26:360-6.
- 4 Alkjaer T, Simonsen EB, Peter Magnusson SP, Aagaard H, Dyhre-Poulsen P. Differences in the movement pattern of a forward lunge in two types of anterior cruciate ligament deficient patients: copers and non-copers. *Clin Biomech (Bristol, Avon)* 2002;17:586-93.
- 5 Andersen TE, Tenga A, Engebretsen L, Bahr R. Video analysis of injuries and incidents in Norwegian professional football. *Br J Sports Med* 2004;38:626-31.
- 6 Angus S. Massage therapy for sprinters and runners. *Clin Podiatr Med Surg* 2001;18:329-36.
- 7 Armstrong RB, Warren GL, Warren JA. Mechanisms of exercise-induced muscle fibre injury. *Sports Med* 1991;12:184-207.
- 8 Arnason A, Sigurdsson SB, Gudmundsson A, Holme I, Engebretsen L, Bahr R. Risk factors for injuries in football. *Am J Sports Med* 2004;32:5S-16S.
- 9 Arnason A, Tenga A, Engebretsen L, Bahr R. A prospective video-based analysis of injury situations in elite male football: football incident analysis. *Am J Sports Med* 2004;32:1459-65.
- 10 Arner P. Microdialysis: use in human exercise studies. *Proc Nutr Soc* 1999;58:913-7.
- 11 Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scand J Med Sci Sports* 2003;13:244-50.
- 12 Askling C, Tengvar M, Saartok T, Thorstensson A. Sports related hamstring strains--two cases with different etiologies and injury sites. *Scand J Med Sci Sports* 2000;10:304-7.
- 13 Aspelin P, Ekberg O, Thorsson O, Wilhelmsson M, Westlin N. Ultrasound examination of soft tissue injury of the lower limb in athletes. *Am J Sports Med* 1992;20:601-3.
- 14 Augustsson J, Esko A, Thomee R, Svantesson U. Weight training of the thigh muscles using closed vs. open kinetic chain exercises: a comparison of performance enhancement. *J Orthop Sports Phys Ther* 1998;27:3-8.
- 15 Augustsson J, Thomee R. Ability of closed and open kinetic chain tests of muscular strength to assess functional performance. *Scand J Med Sci Sports* 2000;10:164-8.
- 16 Balasubramaniam A. Neuropeptide Y (NPY) family of hormones: progress in the development of receptor selective agonists and antagonists. *Curr Pharm Des* 2003;9:1165-75.
- 17 Bangsbo J. Vasoactive substances in the interstitium of contracting skeletal muscle examined by microdialysis. *Proc Nutr Soc* 1999;58:925-33.
- 18 Bennell K, Wajswelner H, Lew P, Schall-Riauour A, Leslie S, Plant D, Cirone J. Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers. *Br J Sports Med* 1998;32:309-14.
- 19 Bijur PE, Silver W, Gallagher EJ. Reliability of the visual analog scale for measurement of acute pain. *Acad Emerg Med* 2001;8:1153-7.
- 20 Braham R, Finch CF, McIntosh A, McCrory P. Community level Australian Football: a profile of injuries. *J Sci Med Sport* 2004;7:96-105.
- 21 Brain SD, Williams TJ, Tippins JR, Morris HR, MacIntyre I. Calcitonin gene-related peptide is a potent vasodilator. *Nature* 1985;313:54-6.

- 22 Burkett LN. Causative factors in hamstring strains. *Med Sci Sports* 1970;2:39-42.
- 23 Byrne C, Eston RG, Edwards RH. Characteristics of isometric and dynamic strength loss following eccentric exercise-induced muscle damage. *Scand J Med Sci Sports* 2001;11:134-40.
- 24 Byrnes WC, Clarkson PM, White JS, Hsieh SS, Frykman PN, Maughan RJ. Delayed onset muscle soreness following repeated bouts of downhill running. *J Appl Physiol* 1985;59:710-5.
- 25 Cappozzo A, Catani F, Croce UD, Leardini A. Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clin Biomech (Bristol, Avon)* 1995;10:171-8.
- 26 Carleson J, Lundeberg T, Appelgren B. Muscle and brain changes of calcitonin gene-related peptide in experimentally induced unilateral rat masseter myositis. *J Orofac Pain* 2004;18:246-52.
- 27 Cavagna GA, Komarek L, Mazzoleni S. The mechanics of sprint running. *J Physiol* 1971;217:709-21.
- 28 Chesterton LS, Barlas P, Foster NE, Baxter GD, Wright CC. Gender differences in pressure pain threshold in healthy humans. *Pain* 2003;101:259-66.
- 29 Clarkson PM, Tremblay I. Exercise-induced muscle damage, repair, and adaptation in humans. *J Appl Physiol* 1988;65:1-6.
- 30 Cohen SP, Mullings R, Abdi S. The pharmacologic treatment of muscle pain. *Anesthesiology* 2004;101:495-526.
- 31 Connell DA, Schneider-Kolsky ME, Hoving JL, Malara F, Buchbinder R, Koulouris G, Burke F, Bass C. Longitudinal study comparing sonographic and MRI assessments of acute and healing hamstring injuries. *AJR Am J Roentgenol* 2004;183:975-84.
- 32 Costill DL, Daniels J, Evans W, Fink W, Krahenbuhl G, Saltin B. Skeletal muscle enzymes and fiber composition in male and female track athletes. *J Appl Physiol* 1976;40:149-54.
- 33 Cramer RM, Langberg H, Teisner B, Magnusson P, Schroder HD, Olesen JL, Jensen CH, Koskinen S, Suetta C, Kjaer M. Enhanced procollagen processing in skeletal muscle after a single bout of eccentric loading in humans. *Matrix Biol* 2004;23:259-64.
- 34 Dadebo B, White J, George KP. A survey of flexibility training protocols and hamstring strains in professional football clubs in England. *Br J Sports Med* 2004;38:388-94.
- 35 Downie WW, Leatham PA, Rhind VM, Wright V, Branco JA, Anderson JA. Studies with pain rating scales. *Ann Rheum Dis* 1978;37:378-81.
- 36 Ekstrand J, Gillquist J. The frequency of muscle tightness and injuries in soccer players. *Am J Sports Med* 1982;10:75-8.
- 37 Ekstrand J, Gillquist J. Soccer injuries and their mechanisms: a prospective study. *Med Sci Sports Exerc* 1983;15:267-70.
- 38 Ekstrand J, Gillquist J, Moller M, Oberg B, Liljedahl SO. Incidence of soccer injuries and their relation to training and team success. *Am J Sports Med* 1983;11:63-7.
- 39 Ekstrand J, Wiktorsson M, Oberg B, Gillquist J. Lower extremity goniometric measurements: a study to determine their reliability. *Arch Phys Med Rehabil* 1982;63:171-5.
- 40 Ericson MO, Nisell R, Ekholm J. Quantified electromyography of lower-limb muscles during level walking. *Scand J Rehabil Med* 1986;18:159-63.
- 41 Eston RG, Mickleborough J, Baltzopoulos V. Eccentric activation and muscle damage: biomechanical and physiological considerations during downhill running. *Br J Sports Med* 1995;29:89-94.
- 42 Faulkner JA. Terminology for contractions of muscles during shortening, while isometric, and during lengthening. *J Appl Physiol* 2003;95:455-9.
- 43 Feuerstein G, Willette R, Aiyar N. Clinical perspectives of calcitonin gene related peptide pharmacology. *Can J Physiol Pharmacol* 1995;73:1070-4.
- 44 Fridén J, Lieber RL. Eccentric exercise-induced injuries to contractile and cytoskeletal muscle fibre components. *Acta Physiol Scand* 2001;171:321-6.

- 45 Friden J, Seger J, Sjostrom M, Ekblom B. Adaptive response in human skeletal muscle subjected to prolonged eccentric training. *Int J Sports Med* 1983;4:177-83.
- 46 Friden J, Sfakianos PN, Hargens AR. Muscle soreness and intramuscular fluid pressure: comparison between eccentric and concentric load. *J Appl Physiol* 1986;61:2175-9.
- 47 Friden J, Sjostrom M, Ekblom B. A morphological study of delayed muscle soreness. *Experientia* 1981;37:506-7.
- 48 Friden J, Sjostrom M, Ekblom B. Myofibrillar damage following intense eccentric exercise in man. *Int J Sports Med* 1983;4:170-6.
- 49 Fried T, Lloyd GJ. An overview of common soccer injuries. Management and prevention. *Sports Med* 1992;14:269-75.
- 50 Gabbe BJ, Finch CF, Bennell KL, Wajswelner H. Risk factors for hamstring injuries in community level Australian football. *Br J Sports Med* 2005;39:106-10.
- 51 Garrett WE, Jr., Mumma M, Lucaveche CL. Ultrastructural differences in human skeletal muscle fiber types. *Orthop Clin North Am* 1983;14:413-25.
- 52 Garrett WE, Jr., Rich FR, Nikolaou PK, Vogler JB, 3rd. Computed tomography of hamstring muscle strains. *Med Sci Sports Exerc* 1989;21:506-14.
- 53 Hawkins D, Hull ML. A method for determining lower extremity muscle-tendon lengths during flexion/extension movements. *J Biomech* 1990;23:487-94.
- 54 Heijne A, Fleming BC, Renstrom PA, Peura GD, Beynon BD, Werner S. Strain on the anterior cruciate ligament during closed kinetic chain exercises. *Med Sci Sports Exerc* 2004;36:935-41.
- 55 Hernandez-Reif M, Field T, Krasnegor J, Theakston H. Lower back pain is reduced and range of motion increased after massage therapy. *Int J Neurosci* 2001;106:131-45.
- 56 Herring SA. Rehabilitation of muscle injuries. *Med Sci Sports Exerc* 1990;22:453-6.
- 57 Hof AL, Van Zandwijk JP, Bobbert MF. Mechanics of human triceps surae muscle in walking, running and jumping. *Acta Physiol Scand* 2002;174:17-30.
- 58 Hoffmann P, Mazurkiewicz J, Holtmann G, Gerken G, Eysselein VE, Goebell H. Capsaicin-sensitive nerve fibres induce epithelial cell proliferation, inflammatory cell immigration and transforming growth factor-alpha expression in the rat colonic mucosa in vivo. *Scand J Gastroenterol* 2002;37:414-22.
- 59 Homonko DA, Theriault E. Downhill running preferentially increases CGRP in fast glycolytic muscle fibers. *J Appl Physiol* 2000;89:1928-36.
- 60 Hubbard TJ, Denegar CR. Does Cryotherapy Improve Outcomes With Soft Tissue Injury? *J Athl Train* 2004;39:278-9.
- 61 Ito M, Kawakami Y, Ichinose Y, Fukashiro S, Fukunaga T. Nonisometric behavior of fascicles during isometric contractions of a human muscle. *J Appl Physiol* 1998;85:1230-5.
- 62 Jacobs R, Bobbert MF, van Ingen Schenau GJ. Function of mono- and biarticular muscles in running. *Med Sci Sports Exerc* 1993;25:1163-73.
- 63 Jacobs R, Bobbert MF, van Ingen Schenau GJ. Mechanical output from individual muscles during explosive leg extensions: the role of biarticular muscles. *J Biomech* 1996;29:513-23.
- 64 Jarvinen MJ, Lehto MU. The effects of early mobilisation and immobilisation on the healing process following muscle injuries. *Sports Med* 1993;15:78-89.
- 65 Jarvinen TA, Kaariainen M, Jarvinen M, Kalimo H. Muscle strain injuries. *Curr Opin Rheumatol* 2000;12:155-61.
- 66 Klingele KE, Sallay PI. Surgical repair of complete proximal hamstring tendon rupture. *Am J Sports Med* 2002;30:742-7.
- 67 Komi PV. Relationship between muscle tension, EMG and velocity of contraction under concentric and eccentric work, in Desmedt JE (Ed). *New Development in Electromyography and Clinical Neurophysiology* 1973;1:596-606.

- 68 Koulouris G, Connell D. Evaluation of the hamstring muscle complex following acute injury. *Skeletal Radiol* 2003;32:582-9.
- 69 Larsson L, Gransberg L, Knutsson E. Torque-velocity relations in the quadriceps muscle of smoking-discordant twins with different fibre type proportions. *Acta Physiol Scand* 1985;123:515-8.
- 70 Lieber RL, Friden J. Selective damage of fast glycolytic muscle fibres with eccentric contraction of the rabbit tibialis anterior. *Acta Physiol Scand* 1988;133:587-8.
- 71 Liemohn W. Factors related to hamstring strains. *J Sports Med Phys Fitness* 1978;18:71-6.
- 72 Ljung BO, Forsgren S, Friden J. Substance P and calcitonin gene-related peptide expression at the extensor carpi radialis brevis muscle origin: implications for the etiology of tennis elbow. *J Orthop Res* 1999;17:554-9.
- 73 Lombard WP. The action of two joint muscles. *Am Phys Ed Rev* 1903;8:141-5.
- 74 Lund I, Yu LC, Uvnas-Moberg K, Wang J, Yu C, Kurosawa M, Agren G, Rosen A, Lekman M, Lundeberg T. Repeated massage-like stimulation induces long-term effects on nociception: contribution of oxytocinergic mechanisms. *Eur J Neurosci* 2002;16:330-8.
- 75 Lundeberg T, Lund I, Dahlin L, Borg E, Gustafsson C, Sandin L, Rosen A, Kowalski J, Eriksson SV. Reliability and responsiveness of three different pain assessments. *J Rehabil Med* 2001;33:279-83.
- 76 Lysholm J, Wiklander J. Injuries in runners. *Am J Sports Med* 1987;15:168-71.
- 77 MacIntyre DL, Reid WD, Lyster DM, Szasz IJ, McKenzie DC. Presence of WBC, decreased strength, and delayed soreness in muscle after eccentric exercise. *J Appl Physiol* 1996;80:1006-13.
- 78 MacIntyre DL, Sorichter S, Mair J, Berg A, McKenzie DC. Markers of inflammation and myofibrillar proteins following eccentric exercise in humans. *Eur J Appl Physiol* 2001;84:180-6.
- 79 Malliaropoulos N, Papalexandris S, Papalada A, Papacostas E. The role of stretching in rehabilitation of hamstring injuries: 80 athletes follow-up. *Med Sci Sports Exerc* 2004;36:756-9.
- 80 Mann RA, Hagy J. Biomechanics of walking, running, and sprinting. *Am J Sports Med* 1980;8:345-50.
- 81 Mann RA, Moran GT, Dougherty SE. Comparative electromyography of the lower extremity in jogging, running, and sprinting. *Am J Sports Med* 1986;14:501-10.
- 82 Mann RV. A kinetic analysis of sprinting. *Med Sci Sports Exerc* 1981;13:325-8.
- 83 Mayhew TP, Rothstein JM, Finucane SD, Lamb RL. Performance characteristics of the Kin-Com dynamometer. *Phys Ther* 1994;74:1047-54.
- 84 Mero A, Komi PV. Electromyographic activity in sprinting at speeds ranging from sub-maximal to supra-maximal. *Med Sci Sports Exerc* 1987;19:266-74.
- 85 Mikkelsen C, Werner S, Eriksson E. Closed kinetic chain alone compared to combined open and closed kinetic chain exercises for quadriceps strengthening after anterior cruciate ligament reconstruction with respect to return to sports: a prospective matched follow-up study. *Knee Surg Sports Traumatol Arthrosc* 2000;8:337-42.
- 86 Mjolsnes R, Arnason A, Osthagen T, Raastad T, Bahr R. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scand J Med Sci Sports* 2004;14:311-7.
- 87 Moran TD, Colmers WF, Smith PA. Opioid-like actions of neuropeptide y in rat substantia gelatinosa: y1 suppression of inhibition and y2 suppression of excitation. *J Neurophysiol* 2004;92:3266-75.
- 88 Naveilhan P, Hassani H, Lucas G, Blakeman KH, Hao JX, Xu XJ, Wiesenfeld-Hallin Z, Thoren P, Ernfors P. Reduced antinociception and plasma extravasation in mice lacking a neuropeptide Y receptor. *Nature* 2001;409:513-7.
- 89 Nilsson J, Thorstensson A. Ground reaction forces at different speeds of human walking and running. *Acta Physiol Scand* 1989;136:217-27.

- 90 Nilsson J, Thorstensson A, Halbertsma J. Changes in leg movements and muscle activity with speed of locomotion and mode of progression in humans. *Acta Physiol Scand* 1985;123:457-75.
- 91 Onuoha GN, Alpar EK. Calcitonin gene-related peptide and other neuropeptides in the plasma of patients with soft tissue injury. *Life Sci* 1999;65:1351-8.
- 92 Orchard J, Marsden J, Lord S, Garlick D. Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. *Am J Sports Med* 1997;25:81-5.
- 93 Ostenberg A, Roos H. Injury risk factors in female European football. A prospective study of 123 players during one season. *Scand J Med Sci Sports* 2000;10:279-85.
- 94 Panni AS, Tartarone M, Maffulli N. Patellar tendinopathy in athletes. Outcome of nonoperative and operative management. *Am J Sports Med* 2000;28:392-7.
- 95 Patel TJ, Das R, Friden J, Lutz GJ, Lieber RL. Sarcomere strain and heterogeneity correlate with injury to frog skeletal muscle fiber bundles. *J Appl Physiol* 2004;97:1803-13.
- 96 Paton RW, Grimshaw P, McGregor J, Noble J. Biomechanical assessment of the effects of significant hamstring injury: an isokinetic study. *J Biomed Eng* 1989;11:229-30.
- 97 Peacock B, Westers T, Walsh S, Nicholson K. Feedback and maximum voluntary contraction. *Ergonomics* 1981;24:223-8.
- 98 Pedersen-Bjergaard U, Nielsen LB, Jensen K, Edvinsson L, Jansen I, Olesen J. Calcitonin gene-related peptide, neurokinin A and substance P: effects on nociception and neurogenic inflammation in human skin and temporal muscle. *Peptides* 1991;12:333-7.
- 99 Peters D, Barash IA, Burdi M, Yuan PS, Mathew L, Friden J, Lieber RL. Asynchronous functional, cellular and transcriptional changes after a bout of eccentric exercise in the rat. *J Physiol* 2003;553:947-57.
- 100 Peterson L, Renström P. Sports injuries. *Prisma* 2003:28-39.
- 101 Petschnig R, Baron R, Albrecht M. The relationship between isokinetic quadriceps strength test and hop tests for distance and one-legged vertical jump test following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther* 1998;28:23-31.
- 102 Pincivero DM, Aldworth C, Dickerson T, Petry C, Shultz T. Quadriceps-hamstring EMG activity during functional, closed kinetic chain exercise to fatigue. *Eur J Appl Physiol* 2000;81:504-9.
- 103 Pincivero DM, Lephart SM, Karunakara RA. Reliability and precision of isokinetic strength and muscular endurance for the quadriceps and hamstrings. *Int J Sports Med* 1997;18:113-7.
- 104 Pincivero DM, Lephart SM, Karunakara RG. Relation between open and closed kinematic chain assessment of knee strength and functional performance. *Clin J Sport Med* 1997;7:11-6.
- 105 Proske U, Morgan DL, Brockett CL, Percival P. Identifying athletes at risk of hamstring strains and how to protect them. *Clin Exp Pharmacol Physiol* 2004;31:546-50.
- 106 Roos EM, Engstrom M, Lagerquist A, Soderberg B. Clinical improvement after 6 weeks of eccentric exercise in patients with mid-portion Achilles tendinopathy - a randomized trial with 1-year follow-up. *Scand J Med Sci Sports* 2004;14:286-95.
- 107 Sallay PI, Friedman RL, Coogan PG, Garrett WE. Hamstring muscle injuries among water skiers. Functional outcome and prevention. *Am J Sports Med* 1996;24:130-6.
- 108 Schafers M, Sorkin LS, Sommer C. Intramuscular injection of tumor necrosis factor-alpha induces muscle hyperalgesia in rats. *Pain* 2003;104:579-88.
- 109 Schmelz M, Luz O, Averbeck B, Bickel A. Plasma extravasation and neuropeptide release in human skin as measured by intradermal microdialysis. *Neurosci Lett* 1997;230:117-20.
- 110 Schwane JA, Armstrong RB. Effect of training on skeletal muscle injury from downhill running in rats *J Appl Physiol*, 1983:969-75.

- 111 Seger JY, Arvidsson B, Thorstensson A. Specific effects of eccentric and concentric training on muscle strength and morphology in humans. *Eur J Appl Physiol Occup Physiol* 1998;79:49-57.
- 112 Seger JY, Thorstensson A. Effects of Eccentric versus Concentric Training on Thigh Muscle Strength and EMG. *Int J Sports Med* 2005;26:45-52.
- 113 Seward H, Orchard J, Hazard H, Collinson D. Football injuries in Australia at the elite level. *Med J Aust* 1993;159:298-301.
- 114 Shalabi A, Kristoffersen-Wilberg M, Svensson L, Aspelin P, Movin T. Eccentric training of the gastrocnemius-soleus complex in chronic achilles tendinopathy results in decreased tendon volume and intratendinous signal as evaluated by MRI. *Am J Sports Med* 2004;32:1286-96.
- 115 Sherry MA, Best TM. A comparison of 2 rehabilitation programs in the treatment of acute hamstring strains. *J Orthop Sports Phys Ther* 2004;34:116-25.
- 116 Silbernagel KG, Thomee R, Thomee P, Karlsson J. Eccentric overload training for patients with chronic Achilles tendon pain--a randomised controlled study with reliability testing of the evaluation methods. *Scand J Med Sci Sports* 2001;11:197-206.
- 117 Simonsen EB, Thomsen L, Klausen K. Activity of mono- and biarticular leg muscles during sprint running. *Eur J Appl Physiol Occup Physiol* 1985;54:524-32.
- 118 Smith LL, Keating MN, Holbert D, Spratt DJ, McCammon MR, Smith SS, Israel RG. The effects of athletic massage on delayed onset muscle soreness, creatine kinase, and neutrophil count: a preliminary report. *J Orthop Sports Phys Ther* 1994;19:93-9.
- 119 Soderkvist I, Wedin PA. Determining the movements of the skeleton using well-configured markers. *J Biomech* 1993;26:1473-7.
- 120 Soderman K, Alfredson H, Pietila T, Werner S. Risk factors for leg injuries in female soccer players: a prospective investigation during one out-door season. *Knee Surg Sports Traumatol Arthrosc* 2001;9:313-21.
- 121 Stanish WD, Rubinovich RM, Curwin S. Eccentric exercise in chronic tendinitis. *Clin Orthop* 1986:65-8.
- 122 Stanley BG, Magdalin W, Seirafi A, Nguyen MM, Leibowitz SF. Evidence for neuropeptide Y mediation of eating produced by food deprivation and for a variant of the Y1 receptor mediating this peptide's effect. *Peptides* 1992;13:581-7.
- 123 Svernlöv B, Adolfsson L. Non-operative treatment regime including eccentric training for lateral humeral epicondylalgia. *Scand J Med Sci Sports* 2001;11:328-34.
- 124 Thorsson O, Hemdal B, Lilja B, Westlin N. The effect of external pressure on intramuscular blood flow at rest and after running. *Med Sci Sports Exerc* 1987;19:469-73.
- 125 Thorsson O, Leander P, Lilja B, Nilsson P, Obrant K, Westlin N. Comparing ultrasonography, magnetic resonance imaging and scintigraphy in evaluating an experimentally induced muscular hematoma. *Scand J Med Sci Sports* 1993;3:110-6.
- 126 Thorsson O, Lilja B, Nilsson P, Westlin N. Immediate external compression in the management of an acute muscle injury. *Scand J Med Sci Sports* 1997;7:182-90.
- 127 Tiidus PM, Shoemaker JK. Effleurage massage, muscle blood flow and long-term post-exercise strength recovery. *Int J Sports Med* 1995;16:478-83.
- 128 Waling K, Sundelin G, Ahlgren C, Jarvholm B. Perceived pain before and after three exercise programs--a controlled clinical trial of women with work-related trapezius myalgia. *Pain* 2000;85:201-7.
- 129 Wang JZ, Lundeberg T, Yu LC. Anti-nociceptive effect of neuropeptide Y in periaqueductal grey in rats with inflammation. *Brain Res* 2001;893:264-7.
- 130 Warrell TW, Perrin DH, Gansneder BM, Gieck JH. Comparison of isokinetic strength and flexibility measures between hamstring injured and noninjured athletes. *J Orth Sport Phys Ther* 1991;13:118-25.

- 131 Weber MD, Servedio FJ, Woodall WR. The effects of three modalities on delayed onset muscle soreness. *J Orthop Sports Phys Ther* 1994;20:236-42.
- 132 Werners R, Pynsent PB, Bulstrode CJ. Randomized trial comparing interferential therapy with motorized lumbar traction and massage in the management of low back pain in a primary care setting. *Spine* 1999;24:1579-84.
- 133 Westing SH, Seger JY. Eccentric and concentric torque-velocity characteristics, torque output comparisons, and gravity effect torque corrections for the quadriceps and hamstring muscles in females. *Int J Sports Med* 1989;10:175-80.
- 134 Wright A, Graven-Nielsen T, Davies, II, Arendt-Nielsen L. Temporal summation of pain from skin, muscle and joint following nociceptive ultrasonic stimulation in humans. *Exp Brain Res* 2002;144:475-82.
- 135 Yack HJ, Collins CE, Whieldon TJ. Comparison of closed and open kinetic chain exercise in the anterior cruciate ligament-deficient knee. *Am J Sports Med* 1993;21:49-54.
- 136 Yarnitsky D, Sprecher E, Zaslansky R, Hemli JA. Multiple session experimental pain measurement. *Pain* 1996;67:327-33.
- 137 Yu JG, Carlsson L, Thornell LE. Evidence for myofibril remodeling as opposed to myofibril damage in human muscles with DOMS: an ultrastructural and immunoelectron microscopic study. *Histochem Cell Biol* 2004;121:219-27.
- 138 Zhang L, Hoff AO, Wimalawansa SJ, Cote GJ, Gagel RF, Westlund KN. Arthritic calcitonin/alpha calcitonin gene-related peptide knockout mice have reduced nociceptive hypersensitivity. *Pain* 2001;89:265-73.

ORIGINAL PAPERS (I-VI)