Lumbar Muscle Fatigue and Recovery

Evaluation of electromyography in patients with long-term low-back pain and in healthy subjects

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STOCKHOLM 2002

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ISBN 91-7349-391-0

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PhD dissertation, Stockholm 2002

Abstract

Background: Lumbar muscle function is considered to be an important component of long-term low-back pain. The change in the median frequency of the power spectrum of the electromyographic (EMG) signal is commonly used to estimate muscle fatigue.

Aim: The main purpose was to evaluate a test method to estimate lumbar muscle fatigue using frequency analysis of the electromyographic signal during isometric contraction.

Methods: In the different studies, 73 healthy subjects participated; 55 of these constituted a reference group which was compared to 57 patients with long-term low-back pain. The subjects performed a back extensor test in seated position: maximal voluntary contraction (MVC) torque, 45 s isometric fatigue contraction at 80% of MVC, 5 s contractions after 1, 2, 3 and 5 min in the recovery period. Surface EMG was recorded from the lumbar muscles bilaterally at spinal levels L1 and L5. To study reliability, this test was repeated five times by 11 of the healthy subjects and once by 20 of the patients. In a further study, 15 of the healthy subjects performed the fatigue test at 40% and 80% of MVC with both 2 cm and 4 cm interelectrode distances. EMG variables were *initial median frequency*, median frequency *slope* (obtained from linear regression of the fatigue contraction) and *recovery half-time* (obtained from non-linear regression of the recovery data). Activity, participation and other health-related factors were estimated by the patients in five questionnaires.

Results: The reliability was somewhat higher for patients (ICC>0.6) than for healthy subjects. The initial median frequency and, to a greater extent, the slope were sensitive to the exerted torque. The patients differed from the healthy subjects by lower MVC torque, higher initial median frequency at L5, and by flatter slope and longer recovery half-time at both lumbar levels. Using logistic regression entering EMG initial median frequency, slope and recovery half-time in combination with MVC, about 80% of the patients and the healthy subjects could be correctly classified. By analyses of individual linear and non-linear regressions, it was found that patients with not significantly negative slopes and/or not exponential-like EMG recovery had lower self-efficacy and more activity limitations. Female patients had significantly flatter slopes, lower physical functioning and self-efficacy than male patients. The results indicate that the ability to fatigue the lumbar muscles in a 80% MVC contraction might be a healthy sign.

Conclusion: The most important findings concerning the validity of the present test are that patients with long term low-back pain and back-healthy subjects could be correctly classified in about 80% of the cases, and that subjective assessments of health-related factors were related to EMG fatigue and recovery.

Key words: Disability, electromyography, exponential, force level, gender, healthy subjects, interelectrode distance, low-back pain, erector spinae, maximal voluntary contraction, muscle fatigue, recovery, reliability, validity.

ISBN 91-7349-391-0

LIST OF PUBLICATIONS

This thesis is based on the following publications, which will be referred to in the text by their Roman numerals I-V. Certain new analyses and results are also added. Contents of published material were reprinted with kind permission from the respective copyright holders.

Study I	Elfving B, Németh G, Arvidsson I, Lamontagne M. Reliability of EMG spectral parameters in repeated measurements of back muscle fatigue. Journal of Electromyography and Kinesiology 1999;9:235-243.
Study II	Elfving B, Németh G, Arvidsson I. Back muscle fatigue in healthy men and women studied by electromyography spectral parameters and subjective ratings. Scandinavian Journal of Rehabilitation Medicine 2000;32:119-125.
Study III	Elfving B, Liljequist D, Mattsson E, Németh G. Influence of interelectrode distance and force level on the spectral parameters of the electromyographic signal recorded from the lumbar muscles. Journal of Electromyography and Kinesiology 2002;12:295-304.
Study IV	Elfving B, Liljequist D, Dedering Å, Németh G. Recovery of electromyograph median frequency after back muscle fatigue analysed using an exponential time dependence model. European Journal of Applied Physiology 2002;88(1-2):85-93
Study V	Elfving B, Dedering Å, Németh G. Lumbar muscle fatigue and recovery in patients with long-term low-back trouble. Submitted for publication.

CONTENTS

ABBREVIATIONS

ANOVA	Analysis of variance
EMG	Electromyography
f_i	Initial median frequency
f	Median frequency
H^+	Hydrogen ion
ICC	Intraclass correlation coefficient
ICF	International Classification of Functioning, Disability and Health
L1	Spinal level at the first lumbar vertebrae
L5	Spinal level at the fifth lumbar vertebrae
MVC	Maximal voluntary contraction
pH	Acidity, concentration of hydrogen ions
Slope	Slope of regression line, i.e. rate of decrease in median frequency during a contraction. “Steep” slope = high rate of decrease “Flat” slope = low rate of decrease
S_w	Standard error of measurement
S_{diff}	Within-subject standard deviation of differences
$t_{½}$	Recovery half-time

1 INTRODUCTION

Lumbar muscle function is considered to be an important component of long-term low-back pain, and there is an increasing need for objective assessment methods. In this thesis, a test method using electromyograhpy (EMG) for estimating lumbar muscle fatigue and recovery is evaluated. Reliability was considered in Study I, III and V. Fatigue and recovery, observed in a reference group of healthy subjects, were analysed in Study II and IV. Finally, in Study V, the validity was investigated by testing the method on patients with long-term low-back pain. Figure 1 illustrates the main concepts in this thesis.

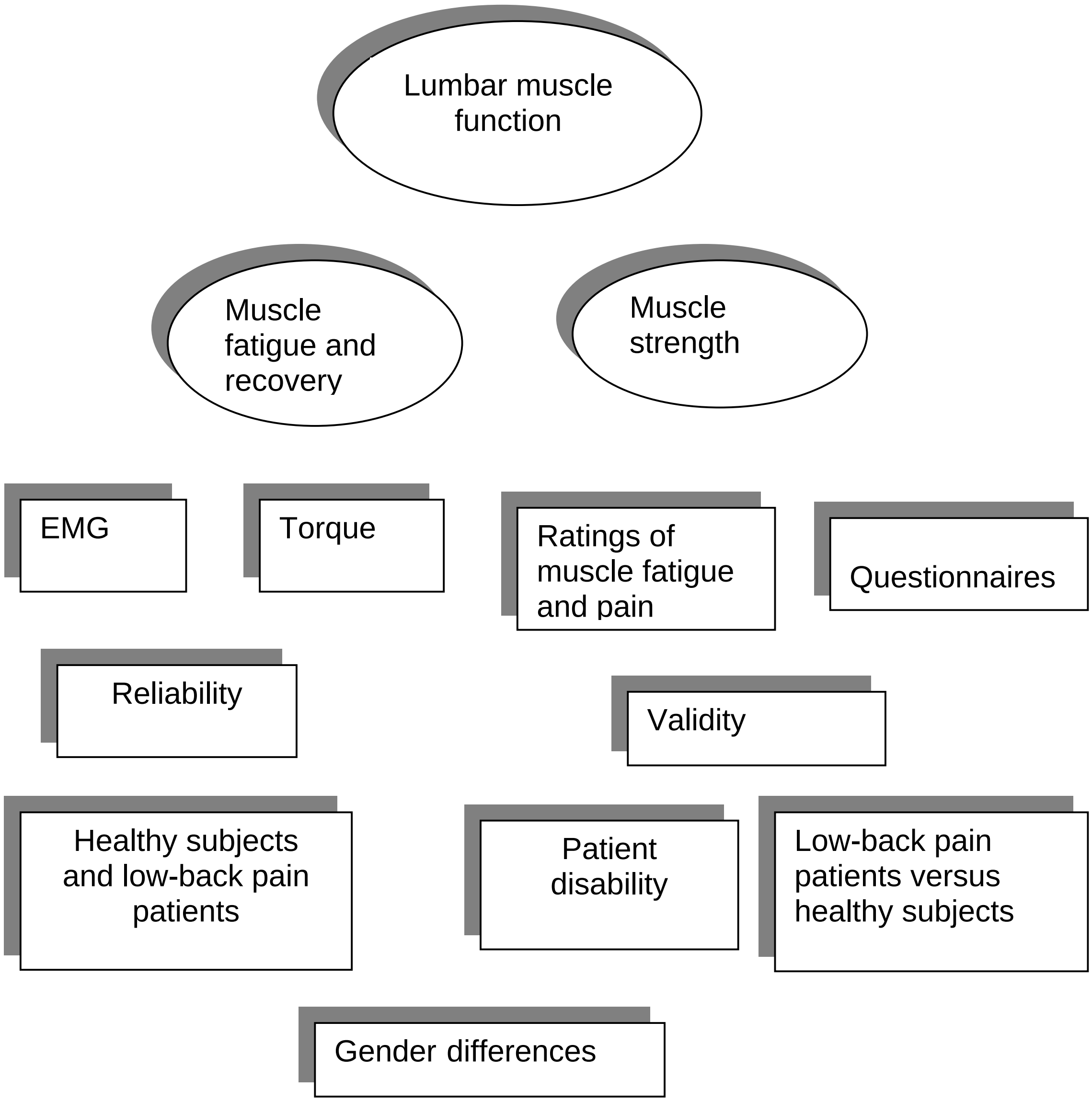

Figure 1. The main concepts and investigated parts in this thesis.

2 LITERATURE REVIEW

2.1 LOW-BACK PAIN

Human beings have had back pain throughout recorded history, but nowadays there is an epidemic of disability in spite of advances in knowledge and resources. The costs due to low-back pain in the Western countries have risen enormously during the latest 15 years [177]. Low-back disorders are the most common cause to chronic illness in men and women up to the age of 64 years [110]. The age of onset of non-specific low-back pain is from the teenage to about 40 years of age, more rarely after 55 years. The risk of experiencing at least one incident of low-back pain during lifetime is 60-70% with no difference between men and women [80,110].

Only about 15% of the patients seeking care for low-back pain get a well defined diagnosis based on pathology. The rest have so called non-specific low-back pain. This is described as a "mechanical" back pain of musculoskeletal origin in which symptoms vary with physical activity [177]. In primary care about 80% of these patients get well regardless of treatment or no treatment, and the rest are prone to develop chronic back pain, which can lead to considerable disability and chronicity [37,39,144]. Research on various kinds of treatments show strong evidence that exercise programs have positive effects on patients with long-term non-specific low-back pain [55,110], but there is still lacking evidence on the best type of exercises and intensity [122]. However, it is clearly shown that inactivity has detrimental affects [24]. Self-care techniques for patients with low-back pain can improve the patient's perception of control and improve long-term outcome [121].

Low-back pain is a symptom from impairments in structures in the lower back, which originates e.g. in muscles, ligaments and discs. One problem is that there is only a weak association between symptoms and diagnostic results, e.g. radiology [37]. Only 36% of healthy people with no history of back pain had normal discs on magnetic resonance imaging of the lumbar spine [61]. The scientific evidence for certain diagnosis, e.g. pain due to degenerative discs, facet joint syndrome, instability, is small. Getting such a diagnosis can, on the contrary, increase the patient´s anxiety, eventually leading to a chronic pain condition and increased disability [110].

Because of the limitations in assessing patients with non-specific low-back disorders by medical diagnosis, the severity could better be judged by physical impairment and activity limitation. Physical impairment is an objective structural limitation, and activity limitation is the resulting loss of function, usually reported subjectively [178]. General recommendations today to prevent long-term disability for people with low-back pain is early activation and restoration of function, even if pain persists [177], and early interventions to minimize sick-leave from work [120].

Classifications of the patients according to the time duration of pain is often used, for example the definitions acute, subacute or chronic low-back pain [19]. Back pain is a sensation of pain or discomfort in the back, with possible radiation. The Paris Task Force on Back Pain [2] defines four categories. In category 1 and 2 the low-back pain is radiating to the gluteal fold or no further than the knee; symptoms may be intermittent or constant and of variable intensity. In category 3 and 4 the pain is radiating below the knee with or without neurological symptoms [2]. The natural history of non-specific low-back pain is that it is a recurrent problem, eventually during a long time span [177] affecting the ability to function in work and personal life [101]. As the word chronic might be associated with negative expectations the word *long-term* is preferred [84].

Low-back pain is a complex disorder where pain, anatomical, physiological, psychological and social aspects are involved. Among physical deficiencies that might cause long-term low-back pain, lumbar muscle function is considered to be one important component. Patients with low-back pain often have reduced isometric back muscle endurance [58,59,66,86,119] as well as reduced back muscle strength [59,149,161], probably as a consequence of disuse and deconditioning related to the back pain.

The deep paraspinal lumbar muscles, e.g. multifidus, have a stabilizing function on the spine, and they are active in maintaining posture [173]. When lumbar muscles are fatigued a decline in performance will increase the risk of injury [152]. This risk is greatest when the spine is exposed to a sudden load [42]. In patients with low-back pain postural control is negatively affected by muscle fatigue [23,85] as well as the ability to sense a change in the lumbar position [160]. Therefore, the study of muscle function is an important part in the research on low-back pain.

2.2 PAIN AND HEALTH-RELATED FACTORS

Non-specific low-back pain is a painful dysfunction in the structures of the spine. Pain is a symptom, not a diagnosis or an illness, and can only be measured through individual subjective assessment [110]. In long-term back pain psychological factors play an increasing role for disability [110]. Beliefs about health may be important determinants of disability and for the outcome of low-back pain [121]. For example, pain-related fear of physical activity can cause avoidance of activity and increased disability [29,83,94]. Disability influences a person’s opinion about himself and the expectations in various situations. Self-efficacy is a personal conviction that one can successfully perform a required task [4]. For example, self-efficacy beliefs in physical capacity has been shown to be a powerful predictor of isokinetic trunk muscle performance [47] and lifting capacity [77]. Moreover, function may be restored even though pain continues as many people go back to work while still experiencing back pain [175]. Reducing negative beliefs about the inevitable consequences of a life with low-back pain has been shown to reduce work absence [159].

With the overall aim to provide a unified and standard language and framework for the description and classification of health and health-related states, the World Health Organisation has created the International Classification of Functioning, Disability and Health (ICF) [1]. The two parts of ICF are
1) Functioning and disability, including a) body functions and structures and
b) activities and participation and
2) Contextual factors including a) environmental and b) personal factors.
Disability is the negative aspect of functioning including a) *impairment*,
b) *activity limitation* and *participation restriction* (problems in involvement in life situations).

A framework according to the ICF linking back pain and occupational activity is given by the Paris Task Force on Back Pain [2], where it is also stated the possibility to have back pain impairment without activity limitation, and to have activity limitation without restriction in participation. Some questionnaires measuring activity limitation and participation restriction are specially designed and recommended for low-back pain patients [6,38,72].

2.3 MUSCULAR STRENGTH, ENDURANCE AND FATIGUE

A muscle contraction depends on a chain of electrical and biochemical events taking place from the brain to the muscle fiber. Any failure along this chain would lead to a loss of force which may characterize fatigue [11]. The physiological mechanism of *central fatigue* would be a declining activation by the central nervous system (brain and spinal cord), resulting in reduced motor unit recruitment and firing rate. If, for example, a force loss during maximal voluntary contraction (MVC) can be restored by electrical stimulation of the muscle, the fatigue apparently had been central [11,43]. *Peripheral fatigue* would be in the motor-unit and could be caused by, for example, impairment in the neuromuscular junction, in the propagation of action potentials along the muscle fiber, or in the excitation-contraction coupling mechanisms [11,43].

Maximal voluntary contraction (MVC) force (isometric) and maximal power output (dynamic) is defined as ”the force generated with feedback and encouragement, when the subject believes it is a maximal effort” [176] (p220). Muscle fatigue caused by muscular work depends on the amount of effort exerted and the duration of the exertion [21]. Localized muscle fatigue is defined as “any exercise-induced reduction in the ability of a muscle to generate force or power, it has peripheral and central causes”. Rest reverses it [49] (p1732)[176] (p220).

The concept of fatigue may also be divided into three subsets: *Subjective fatigue* (decline of alertness, mental concentration and motivation), *objective fatigue* (decline in work output) and *physiological fatigue* (changes in physiological processes) [31]. For example, during an isometric contraction the muscles are continuously fatiguing, but at some time the force can no longer be maintained, i.e. a ´the failure point` is reached [31]. This is easily observable and might therefore be called objective fatigue. However, from the start of the contraction there are changes in the metabolic processes in the muscle, which can be assessed with for example EMG, which would thus be an objective way to measure physiological fatigue. These physiological changes may, for example, include the accumulation of lactate and other metabolites, the slowing down of muscle fiber conduction velocity and the slowing down muscle fiber contractile speed. It is not clear which of these determine performance and which are simply by-products [12]

Concerning subjective fatigue, tests of muscle strength and endurance are influenced by motivation [11,102], including tolerance of pain and discomfort [45] and fear of pain [29,174]. Subjective feelings of fatigue, exertion or pain during a fatiguing task can be assessed with rating scales, e.g. the commonly used category rating scale by Borg [18].

2.4 RECOVERY FROM MUSCLE FATIGUE

Muscle strength recovers more rapidly from isometric work than muscle endurance after local muscle fatigue [130,143]. There are indices that recovery from fatiguing muscular work to a non-fatigued state may be regarded as, at least approximately, an exponential process of time [130,143], i.e. the rate of recovery is typically highest at the beginning of the rest period and then successively slows down. This is also found for heart rate, breathing depth, systolic blood pressure, oxygen uptake, blood lactate elimination [136] and metobolic changes in a muscle during recovery [147]. In localized muscle fatigue the removal of lactate will be fast when the contraction ends and the circulation is quickly restored. Lactate removal will take longer time after exhaustive work with many muscle groups, due to lactate in the circulating blood [31].

2.5 MUSCLE FIBER COMPOSITION

Muscle fibers can be divided into type I fibers (slow, oxidative, fatigue resistant) and type II fibers (fast fibers). Type II fibers are predominantly activated at higher force levels [27,46]. The type II fibers can be subdivided into type IIA and IIX fibers (IIX fibers were previously called IIB), where type IIX are fast, glucolytic, fast fatigable, and the type IIA fibers are fast, oxidative-glucolytic, fatigue resistant, e.g. have intermediate characteristics between the two extreme types type I and type IIX [87,99]. The proportion of type I fibers in muscles can vary between 10 and 90%. It is higher in muscles with a postural function, e.g. the back muscles [165]. Differences between individuals in fiber type distribution are largely determined by a genetic code. The transformation of fiber types as an influence of training is indecisive but might be possible following chronic and specific types of physical activities [99]. However, training can to a great deal affect the metabolism of muscles. The oxidative capacity of the type I fibers can be greatly increased with endurance training, and the glucolytic capacity in type II fibers increases following anaerobic training [46].

In general, regarding extremity muscles, type I fibers are smaller in diameter than type II fibers [99]. However, the back muscles are different from extremity muscles in this respect. In men each fiber type is of similar mean size, whereas in women the type I fibers are reported to be larger than the type II fibers [92,165]. Both men and women have a dominance of type I fibers (54-73%) in the back muscles [117].

Studies on low-back pain patients have mostly been made on patients with disc herniation, and these studies have shown type II fiber atrophy and structural changes at the involved lumbar level [133,179,181] and also type I fiber atrophy [179]. Pathological changes in the muscle fibers of chronic back pain patients have also been observed [87,95,117]. However, interpretation of results from various studies are ambiguous concerning changes in fiber type proportion or atrophy, and results are highly dependent on the selection of the study group. Studies of muscle biopsies might be influenced by the age of the patients investigated, their pain duration, their habitual exercise level or inactivity [87]. There is still no clear answer to the question regarding *cause or effect* of fiber type changes in low-back pain.

The most consistent findings, however, are a decreased cross-sectional area of the deep paraspinal muscles in patients with long-term low-back pain [59], with an atrophy of type II fibers but no atrophy of type I fibers [117,154]. A reason for this would be that patients with back pain probably avoid strong back muscle contractions which would activate the type II fibers. Intensive strength training of the back muscles has been shown to increase the size of the type II muscle fibers [134]. The type I fibers of the deep paraspinal muscles, on the other hand, might be activated due to a pain-induced muscle spasm, and due to an increased role in providing stability to the lumbar spine due to atrophy of other back muscles [28,117], although this muscle spasm model is not always supported [26]. However, Mannion et al. [95] have found, in patients with long pain durations, an increase in IIX fibers, i.e. more fatigable fibers. This might predispose an individual to injury and appropriate training should be of great importance to restore the muscles [95,117].

2.6 SURFACE ELECTROMYOGRAPHY

2.6.1 Recording the EMG signal

Muscles under contraction give rise to electric signals which can be recorded by means of EMG. Bipolar surface electrodes are commonly used, with the two electrodes ideally lined up in a direction parallel to the muscle fibers. The main point of the bipolar technique is that background noise is reduced. The EMG signal is an electric potential difference between the two electrodes, continuously varying with time. It originates from a chemical-electrical change (action potential), running along the muscle fiber with a certain conduction velocity. The registered electric signal will then be a superposition of action potentials from many muscle fibers belonging to several motor units; it appears as a rapid and irregular oscillation. The signal is amplified and band-pass filtered, usually between 10 and 500 Hz, since most EMG signal frequencies are well below 500 Hz. The sampling frequency should be twice the maximum band-pass filter frequency, i.e. at least 1000 Hz to ensure that the EMG signal is recorded without the so-called aliasing (a numerical effect due to the sampling process itself).The sampled signal amplitude is then converted from analogue to digital form. Data are stored in a computer for further analysis. Examples of some of the more easily read references on EMG are [118,168,182].

2.6.2 Analysis of EMG signals

Inspection of the raw, sampled signal is useful for detection of signal errors. The EMG signal can be analysed basically in two ways or domains, the *time domain* and the *frequency domain*, depending on the purpose of the study [5,150,182]. To determine the contraction level or the contraction sequence of specific muscles during certain movements the analysis would be in the time domain. If the focus of interest is muscle fatigue the analysis would rather be in the frequency domain. The amplitude of the myoelectric signal as well as the frequency content of the signal undergoes changes during a submaximal isometric fatiguing contraction. Near the end of the contraction the amplitude will rise [31,176]. The size of the amplitude reflects the number of active motor units and the firing rate. It has been suggested that, to maintain the contraction force, the rise in amplitude is probably due to recruitment of new motor units and to synchronization of the motor unit firing rate [31]. However, since a rise in amplitude also indicates increased muscle load, this variable is not good as a single estimator of localized muscle fatigue [176,182]. Analysis of frequency is preferable. The mathematical method giving the frequency spectrum is called Fourier analysis. There is a rapid algorithm for this called the *Fast Fourier Transform (FFT)* [118,182].

2.6.3 Frequency (Fourier) analysis

An electric voltage signal may for example oscillate harmonically, i.e. as a sine or cosine wave. Each such wave has a certain frequency and a certain amplitude. In general, a measured electric signal may be regarded as a superposition of many such waves. In a frequency analysis this superposition of waves is split up in its components and may be shown as a power spectrum, which essentially is a kind of histogram [166]. The power spectrum is usually calculated for short time intervals (0.5 to 2s) [104]. To obtain a single variable from the power spectrum, the *median frequency,* which divides the area of the spectrum in two equal halves, or the *mean frequency,* which is the mean value of the frequencies weighted with their respective power, is often calculated. The median frequency has been shown to be less sensitive to noise and more sensitive to modifications that occur in the electric signal during sustained contractions and would therefore be better to monitor muscle fatigue [104,156].

2.6.4 EMG signal during fatigue and recovery

During sustained isometric contraction the EMG signal undergoes a change in shape (the wave form expands in time) which results in a compression of the power spectra to lower frequencies. Thus, the median and the mean frequency will decrease during the contraction as a sign of myoelectric manifestation of muscle fatigue [31,104,139]. The median frequency change over a short contraction period can be analysed by linear regression [90,105,118]. The (usually negative) inclination of the regression line (often called the *slope*) will then indicate the *fatigue rate*. The y-intercept of the regression line is often used as the *initial median frequency*, i.e. at the *start of the contraction* [118,140]. Figure 2 shows a typical example.

The decrease of the EMG median (or mean) frequency during contraction has been studied for about 40 years [60,182]. The reason for this decrease has been attributed mainly to a reduced conduction velocity of the action potential along the muscle fiber, which in turn is related to a decrease in pH due to accumulation of lactic acid and other metabolites [32,60]. Thus, we might expect the decrease of median frequency to be associated in particular with the activation of the glucolytic type II fibers [51,71,106]. Muscle fiber conduction velocity is also related to the type and diameter of muscle fibers. A larger muscle diameter appears to be related to a higher conduction velocity [32,106].

Accordingly, there was a significant correlation showing larger type I fiber area to be related to less EMG fatigue rate (flatter slope) for the erector spinae, where also women were more fatigue resistant than men [76,93]. Correlations on extremity muscles have also shown that larger fibers were related to a higher initial median or mean frequency and a steeper slope [52,75]. Furthermore, patients with 95-100% type I fibers have shown an absence of decrease in muscle fiber conduction velocity during fatiguing contraction, and this was related to lack of lactate formation [82].

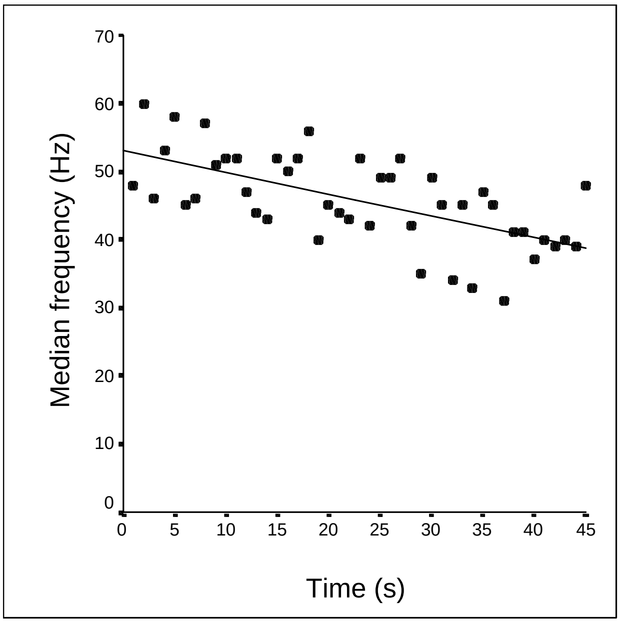

Figure 2. Median frequency decrease during the 45 s back muscle contraction. The figure shows a typical example from one individual and one recording site; the slope is –0.32 Hz/s and the decrease is significant ($p<0.01$).

During recovery, the median frequency returns fairly rapidly to approximately the pre-fatigue value; recovery times about 1-6 min are reported [7,20,54,74,130,131,162]. It should be noted that in order to measure recovery with EMG the muscular repose has to be interrupted by short contractions. The recovery of the median frequency has been observed to occur exponentially [54,74]. A suitable analysis method is then non-linear regression [170].

2.6.5 Other factors influencing the EMG signal

Several factors that can influence the EMG signal have to be considered, e.g. electrode location, interelectrode distance, amount of tissue between the electrodes and the active fibers, nearness to innervation zones, crosstalk from nearby muscles, number and type of active motor units, type of contraction and the force level [32,56,103,106].

Several experimental studies have shown that an increase in interelectrode distance in general shifts the power spectrum towards lower frequencies [13,50]. This is conveniently expressed as a decrease in the median or the mean frequency. For back muscles this has also been shown [138,180], although not consistently [91].

For a bipolar electrode configuration parallel to muscle fibers of "infinite" length and not located near innervation points, the effect of the interelectrode distance d on the power spectrum $P(f)$ is that the spectrum is proportional to a factor $\sin^2(\pi f \cdot d/v)$ (bipolar filter factor), where f is the frequency and v is the conduction velocity [81]. In reality, the dependence of the power spectrum on d is somewhat more complex, due to factors such as the distribution of conduction velocities, finite muscle fiber length, varying muscle fiber directions and nearness to innervation points. However, the bipolar electrode filter factor appears to be a reasonable first approximation in describing the effect of interelectrode distance.

2.6.6 Previous fatigue studies on back muscles using EMG

Different test positions have been used in studies of isometric back muscle fatigue. Most common is the Sørensens test, i.e. prone unsupported trunk horizontally [64,89,107,116,125,153,167] or modified with the hips flexed 40º [34]. The force exerted by the back muscles in keeping the trunk horizontally is about 40-50% of MVC [58,90,148]. The hip extensors fatigue as well during the Sørensens test [64]. Other test positions used are back extension in standing position [140], semistanding [129] or sitting position [171], and lateral bending in standing [163], with simultaneous monitoring of force feedback. In seated position the hip extensors are also involved, though the lumbar muscles are activated to a higher degree [66]. During strength measurements in these positions pelvis stabilisation is crucial to get accurate activation of the lumbar muscles [25].

It is common to use several electrode locations on the erector spinae to measure different portions of the muscle [140]. In general, healthy subjects seem to show no difference in slope between the right and the left side of the erector spinae in isometric contractions [89,125]. However, the slope at the caudal parts of the erector spinae seems to be larger than for the more cranial parts [116,140].

The EMG slope has been shown to be steeper for men than for women in Sørensens test [34,64,89,90,125,169]. There was no gender difference for the initial median frequency reported [34,90,125].

Assessing patients with low-back pain using EMG fatigue variables has shown that these patients usually have a steeper slope when compared to healthy persons [98,140], though results are not unanimous [129]. Furthermore, the slope has been shown to become less steep after muscular training [98,141]. The EMG median frequency has been used to discriminate between subjects with and without low-back pain [70,140] and between physically active and passive patients with low-back pain [9]. The recovery after one minute of rest after a fatiguing contraction was a strong discriminator for identifying persons with low-back pain [129,142]. Furthermore, patients with low-back pain and healthy controls were better identified at 80% MVC contractile level compared to lower force levels [140]. However, not all reports are positive to the discriminating ability of the slope, because a large overlap in the ranges of the slope values for healthy subjects and patients with low-back pain leads to a poor discriminating ability on an individual basis [98].

2.7 RELIABILITY

The concept of reliability is a way to reflect the amount of error, both random and systematic, inherent in any measurement [155].

Reliability can be calculated in terms of a *quantitative measure* of variability, the *standard error of measurement* S_w, which is the within-subject standard deviation. To obtain the S_w, a reliability study has to be made preferably on a sample from the population on which the future measurements are going to be used. This may consist in making repeated measurements under constant conditions.

The analysis of variance (ANOVA) with repeated measures is used to calculate the different sources of variation: the variance between-subjects and the variance within-subject. The latter is split up in systematic and random (error or residual) variances. The S_w will then be the square root of the error variance term or of the within-subject variance term (including the systematic variance) [15,22,135].

In a clinical situation it is appropriate to use *the within-subject standard deviation of the differences (S_{diff})* given by $S_{diff} = \sqrt{2} * S_w$ [15]. The difference between two measurements on the same subject is said to be statistically significant at 0.05 level if the difference is larger than 1.96* S_{diff} [14,15,135]. How large a S_w or S_{diff} value that can be tolerated is a clinical question. It depends on what we are measuring and the expected outcome differences.

The S_w could also be contrasted to the variance among the individuals assessed [155]. One way to do this is to calculate a ratio of variances essentially based on the variance between-subjects as compared to the variance within-subjects. This ratio is the *intraclass correlation coefficient (ICC),* which is a *relative measure* in contrast to the measure of S_w. A high ICC (≈1) indicates a small within-subject variance relative to the between-subjects variance. For example an ICC of 0.80 means that 80% of the variance in scores results from the variance among subjects. There are different ways of calculating this coefficient depending on the experimental design, and on whether the ICC is calculated from individual data or mean values [146,155]. Moreover the ICC will depend on the composition and variance of the test group, which illustrates that ICC has no absolute meaning [109]. Therefore, caution should be taken when comparing ICC:s for different populations, e g. patients and healthy subjects. As a consequence, the ICC is difficult to interpret clinically. There is different information in the S_w and ICC. Both are recommended since they are complementary [68,132].

In reliability studies of frequency parameters, results are not easy to compare since methodology often varies. Between-days studies of reliability on healthy subjects reporting S_w and ICC indicate in general good reliability for the initial median frequency but low reliability for the slope [111,126,128]. Some studies report satisfactory ICC for the slope combined with a rather high S_w [115,171], and some report high reliability [36,73,90]. In a recent study attempts have been made to increase reliability by using mean values of different recording sites [73,79]. Since the median frequency slope depends on metabolic processes during fatigue development, and a normal metabolic variability of at least about 20% should be considered [8], a lower reliability for the slope than the initial median frequency could be expected.

2.8 VALIDITY

Validity, in short, is the extent to which a measurement reflects what it is intended to measure. Streiner and Norman [155] emphasise that various types of validity are in fact addressing the same issue of the degree of confidence we can place on inferences about people based on measurement results. The slope of median frequency is said to be an objective measure of muscle fatigue, but how should this be regarded in a clinical context? Do we expect patients with low-back pain to have more fatigable muscles (in terms of steeper slope) than healthy people? In that case we would expect a difference in slope between patients with low-back pain and healthy subjects. If there is no difference, either the test method is too unreliable to detect a difference, or there is no real difference, i.e. low-back pain is not related to myoelectric manifestations of muscular fatigue. Another way to test validity would be to see how muscle fatigue, measured as the slope of median frequency, effects pain and activity of patients with low-back pain. Do patients with more fatigable lumbar muscles show a steeper slope, and do they have more activity limitations? Only a few studies have assessed the relationship between activity limitations and EMG spectral variables and these have shown low correlations [66,94]. Patients with low-back pain classified as "avoiders" had spectral changes that differed from patients classified as "confronters" and from healthy control subjects [9].

3 AIMS

The general aim of this thesis was to evaluate a test method to estimate lumbar muscle fatigue in patients with long-term low-back pain, using frequency analysis of the electromyographic signal during isometric contraction in seated position.

Objectives addressed in the separate studies were

- to assess the reliability of the EMG spectral variables recorded during fatigue and recovery, the MVC torque and the subjective ratings of fatigue during the test (Study I, IV, V)

-to further study some aspects of reliability and methodology by investigating the influence of contraction time, interelectrode distance and force level on the EMG spectral variables (Study II, III).

- to validate the test method by comparing long-term low-back pain patients with a reference group of healthy subjects (Study II, IV, V).

- to relate the EMG spectral variables recorded during fatigue and recovery to health-related factors for patients with long-term low-back pain for further validation (Study V).

4 METHODS

4.1 STUDY SAMPLES

4.1.1 Healthy subjects (Study I-V)

A total of 73 healthy subjects participated in the studies. The characteristics of the subjects are shown in Table 1. The reference group of 55 subjects, which were compared with the patients, had a mean age of 36 years (range 21-57). All healthy subjects were recruited on a voluntary basis and had no history of periodic low-back trouble. They were students or employed in various professions (e.g. health care, teachers, office work, manual work).

4.1.2 Patients with long-term low-back pain (Study V)

The 57 patients, mean age 39 years (range 22-62) were recruited consecutively from physiotherapy clinics in Stockholm.
Inclusion criteria were:
- Low-back pain that restricted functioning; referred pain not distal to the knee.
- Low-back pain present on at least half of the days in a 12-month period in a single or in multiple episodes [175]
- Good understanding of the Swedish language

Exclusion criteria were:
Previous surgery, symptoms of nerve root engagement (i.e. pain distal to the knee), serious neck pain, spondylolistesis, spinal stenosis, inflammatory disease or cancer disease.

Mean (SD) pain duration of the patients was 10 (7) years with a range from 0.5-29 years. One man and five women had been on sick-leave from work, for short periods of time, varying between three weeks and eight months during the preceding year. Only one man was on sick-leave since one year. The majority of the patients were working full time (e.g. office work, manual work, health care, teachers).

4.2 INSTRUMENTS

4.2.1 Back extension device (Study I-V)

The back extension test was performed in a seated position in a back extension training and testing device (David Back Extension 110, David International Ltd, Vantaa, Finland). When seated, the pelvis, the lower back up to L3-L4 level of the spine, the hips and the knees were securely fixed. The seat was adjustable for each individual. The resistance pad, against which the subject pressed backwards, was at the level of the scapula. A display unit (David International Ltd, Vantaa, Finland) in front of the subject continuously showed the torque in newtonmeter (Nm) as a feedback (Fig. 3).

Table 1. Characteristics of the subjects in the different studies given as mean and standard deviation (SD). P-values from t-tests for differences between the patients and the healthy reference group is shown.

Variable	Gender	Study I	Study III	Study II+IV+V	Study V	P-value
Subjects		Healthy	Healthy	Healthy ref. group [1]	Patients	Diff. patients / healthy ref. group
Number	Men	3	4	28	27	
	Women	8	11	27	30	
Age (yr)	Men	35 (9)	29 (5)	35 (11)	39 (12)	0.19
	Women	35 (12)	28 (9)	37 (12)	38 (10)	0.56
BMI (kg/m^2)	Men	26.4 (2.5)	24.1 (4.3)	24.9 (2.5)	24.1 (2.0)	0.22
	Women	21.4 (2.4)	21.1 (1.7)	22.0 (1.9)	23.7 (4.4)	0.07

[1] For 8 healthy subjects, the first of six measurements from Study I was also used in Study II+IV+V.

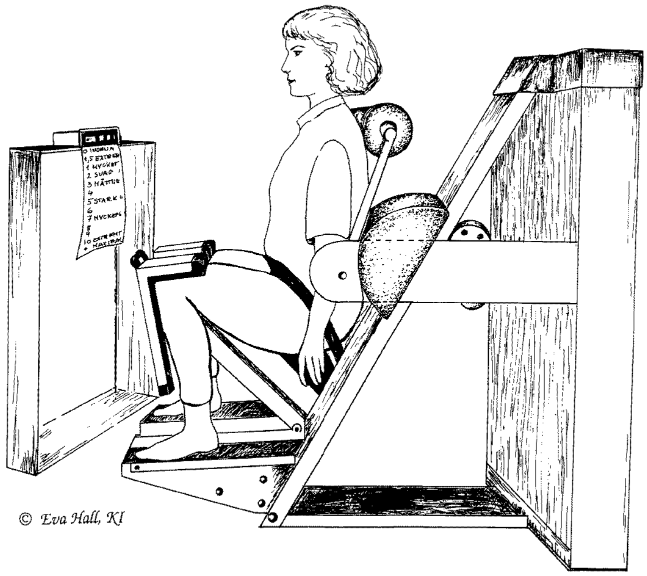

Figure 3. Subject in position for isometric trunk extension. A display unit in front of the subject continuously showed the applied torque.

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4.2.2 Surface EMG (Study I-V)

Electrical activity was recorded from the back extensor muscles at the levels of the first (L1) and the fifth (L5) lumbar vertebrae on the right and the left side. Disposable Ag/AgCl surface disc electrodes were used (Blue Sensor N-00-S, Medicotest A/S, Denmark). The skin was cleaned with alcohol and the electrodes were applied next to each other with an interelectrode distance of 2 cm in the direction of the muscle fibres. The electrodes were placed about 3 cm laterally to the spinous process. The reference electrode was placed on the iliac crest (healthy subjects) or on 3the left lateral malleolus (patients) (Blue Sensor VL-00-S) (Fig. 4).

The EMG signal was recorded from the four electrode locations via a telemetric system (Telemyo 16; Noraxon, USA). The sampling frequency was 1000 Hz and the bandwidth of the input electronics was 10-800 Hz (this is discussed later). EMG analysis was made using software from Noraxon (MyoResearch 97, Noraxon, USA). All raw EMGs and power spectra were inspected. Obvious disturbances in a recording and/or abnormally high frequencies caused some data to be rejected. The median frequency of the power spectrum was calculated for each 1 s interval of the recorded signal by Fast Fourier Transformation.

Figure 4. Electrode position of the four pairs of electrodes on the lumbar muscles.

4.2.3 Borg CR-10 scale (Study I-V)

The healthy subjects rated back muscle fatigue and the patients rated lumbar pain on the Borg category-ratio scale [17,18]. The ratings were made at 15, 30 and 45 s during the fatigue contraction and directly after each recovery contraction.

4.2.4 Questionnaires (Study V)

Before performing the fatigue test five questionnaires were answered by the patients:

1. *The Short Form-36 Health Survey (SF-36)* [158] is a generic health survey, not designed for any special patient category, but it is recommended in studies of back pain [16]. It includes 36 questions. A high score always means better functioning and health or less pain. The result will be presented as sum scores for eight subscales each including a different number of questions: Physical Functioning, Role Physical, Bodily Pain, General Health, Vitality, Social Functioning, Role Emotional, and Mental Health. Some of the questions were analysed separately. There is also Reported Health Transition, i.e. the general health compared to one year ago.
2. *The Roland-Morris Back Pain Disability Questionnaire* [63,137] consists of 24 statements about the functional status ´today` to be answered with ´yes` or ´no`. A higher score means more ´yes` answers and thus a higher degree of activity limitation (scores 0-24).
3. *The Back Beliefs Questionnaire* [159] measures general beliefs about the inevitable consequences of future life with low-back pain and can be used irrespective of current or previous experience with low-back pain. The statements are scored from 1-5 depending on degree of agreement. Minimum score is 9 and maximal score is 45. A high score means positive attitudes towards functioning with low-back trouble. The questionnaire was translated into Swedish by us (Nowakowski M, Shadburn H, Elfving B. Unpublished data, Neurotec department, Division of Physiotherapy, Karolinska Institutet, Stockholm, Sweden).
4. *The Self-Efficacy Scale* [47] assesses self-efficacy beliefs specifically related to eight basic physical activities, i.e. walk, run, carry bags, stand (in line), cycle a bike, sit in an arm-chair, sit at a table, work in a forward bent position. For each item the belief about the length of time the activity can be performed is to be estimated on a scale from 1-8, where one is ´2 min` and eight is ´more than 45 min`. Thus a high score means high self-efficacy beliefs. The questionnaire was translated into Swedish by Johansson et al. [62].
5. *The Oswestry Low-back Pain Disability Questionnaire* [48] covers 10 domains: pain intensity, personal care, lifting, walking, sitting, standing, sleeping, sex life, social life and travelling; for the situation ´today`. For each domain there is a scale of six statements, where zero is ability to perform the activity without pain and five is inability to perform the activity because of pain. Higher score means higher degree of activity limitation (score 0-5). A sum score (%) can be calculated: total score/total possible score $*$ 100.

4.3 EXPERIMENTAL DESIGN (STUDY I-V)

The subject performed isometric trunk extension against the resistance pad. Before the test, the subject performed an isometric contraction at a low torque level to learn to maintain a constant torque aided by the visual feed-back system. Then, MVC was determined from three trials with one minute rest in between. The mean of the two highest values was used as the

MVC value. The main test consisted of recording the EMG signals during an isometric 45 s fatiguing contraction at 80% MVC, followed by a recovery process which was measured by recording the EMG signals during 5 s contractions at 80% MVC, performed at 1 min, 2 min, 3 min and 5 min after the end of the fatigue contraction.

In **Study II, III, IV and V** each subject performed the test once. In addition, in **Study V**, 20 of the patients performed the test on a second occasion after 1-6 days. In **Study I**, a total of six tests were performed by the subjects (n=11) on three different days with an average of five days (range 2-13) in between; each day the test was made in the morning and in the afternoon with the electrodes remaining in position between the two tests made on the same day.

4.4 DATA ANALYSIS OF EMG FATIGUE AND RECOVERY

4.4.1 Fatigue phase

Study I-V. The fatigue contraction was analysed by linear regression analysis of the median frequency f as a function of time t, from $t = 0$ to $t = 45$ s. For each recording the *initial median frequency* f_i was defined as the intercept at $t = 0$. The rate at which the median frequency changed during contraction, briefly called the *slope*, was calculated as the slope of the regression line (Hz/s). It was also normalised to f_i and given in (%/s). Typically the slope was negative indicating a decrease.

Study IV, V. We also checked whether the slope was significantly negative, i.e. negative and significantly different from zero ($p<0.05$). Slopes which were significantly negative will be referred to as *fatigue* and slopes not significantly negative as *non-fatigue* or *absent fatigue*. Since muscular fatigue can have many aspects, it is pointed out that these definitions of *fatigue* and *non-fatigue* are estimates of *a myoelectric manifestation of fatigue (EMG fatigue).*

Study V. The subjects were divided in two groups according to the occurrence of significantly negative slopes during contraction. The *fatigue group* had significantly negative slopes on 3 or 4 recording sites. The *non-fatigue group* had *not* significantly negative slopes on 2, 3 or 4 recording sites.

4.4.2 Recovery phase

Study IV, V. The analysis of the recovery was made using non-linear regression, assuming an exponential time dependence of the recovery phase. Input data in the non-linear regression were, for each recording site, either data from individual recordings (f_e (at the end of the contraction), f_1 (after 1 min of recovery), f_2 (after 2 min) f_3, f_5, f_i) or mean values ($\langle f_e \rangle$, $\langle f_1 \rangle$, $\langle f_2 \rangle$, $\langle f_3 \rangle$, $\langle f_5 \rangle$, $\langle f_i \rangle$) for a group or subgroup of subjects. The coefficient of determination R^2 obtained from the regression analysis represents the explanatory value of the exponential recovery model. We calculated a recovery half-time $t_{½}$, i.e. the time at which the f had recovered by 50% according to the fitted exponential curve.

In most cases in the analysis of individual recovery data f_e, f_1, f_2, f_3, f_5, f_i the exponential model could be fitted to the input data, giving a $t_{½}$ and an asymptotic standard error. In some recordings, however, the input data showed no exponential-like recovery or fluctuated so much that the exponential model was not applicable. Criteria which were used to define the model as *not* applicable were the following: *t½* and/or asymptotic standard error not found; *t½* excessively large (>1 h); recovery process inverted, i.e. slightly decreasing *f*, typically following a not significantly negative slope.

Study V. Subjects for whom the exponential recovery model was applicable to recovery data from 3 or 4 recording sites were selected to the *exponential recovery group*. Subjects for whom the model was not applicable on 2, 3 or 4 recording sites were selected to the *non-exponential recovery group.*

4.5 STATISTICAL METHODS

An overview of the statistical methods used in the five studies is shown in Table 2. All statistics were made using the SPSS statistical package (SPSS Sweden AB). For interval/ratio data, normal distributions were checked with histograms, and sometimes, as a complement, tested with the one-sample Kolmogorov Smirnov test. The initial median frequency, MVC torque, and recovery half-time were ratio data; the slope was interval data. However, the recovery half-time had a positively skewed distribution and was log transformed if parametric tests were used. The Borg ratings and questionnaire scores were considered ordinal data.

Table 2. Statistical methods used in the different studies.

Statistical test	Study I	Study II	Study III	Study IV	Study V
ANOVA repeated measures	X	X	X		X
ICC	X				X
Friedman test	X			X	
Student's unpaired t-test		X			X
Mann-Whitney U-test		X			X
Kruskal-Wallis test					X
Chi-square test					X
Pearson´s correlation coefficient		X			X
Spearman´s correlation coefficient		X		X	X
Linear regression	X	X	X	X	X
Non-linear regression				X	X
Logistic regression					X

Multivariate analysis of variance (ANOVA) with repeated measures [57,123] was used to study reliability. Standard error of measurement S_w was calculated as the square root of the total within-subject variance, the variance between-days and the variance within-day, respectively. The intraclass correlation coefficient ICC 1.1 was used [132,146], i.e.
ICC 1.1 = BMS-WMS / BMS + (k-1)WMS
where BMS=between-subjects mean squares, WMS= within-subject mean squares, and *k* is the number of measurements.

Multivariate ANOVA with repeated measures was also used to study differences between electrode sites, contraction time, force level and interelectrode distance. Between-subject factors in the ANOVA was used for differences between patients/healthy and men/women; as a complement Student' s unpaired t-test was also used. Friedman' s test or Wilcoxons rank sign test was used for ordinal data and not normally distributed data. For ordinal data, between groups differences were tested with Mann-Whitney U-test or Kruskal-Wallis test.

To study correlation Person's correlation coefficient *r* and Spearman's rank correlation coefficient r_s was used. The following descriptive terms for correlation are used:
.00-.25 little, if any
.26-.49 low correlation
.50-.69 moderate correlation
.70-.89 high correlation
.90-1.00 very high correlation [41].

Binary logistic regression (dependent variable patients/healthy) was used to discriminate between the patients and the healthy subjects.
Significance level in hypothesis testing was set at $p<0.05$.

4.6 ICF CLASSIFICATION

The ICF classification [1] was considered for the variables investigated and the assessment methods (Table 3).

Table 3. The ICF domains and the assessment methods used.

ICF domains	Assessment method
Impairments	
Muscle fatigue	EMG
Recovery	EMG
Back muscle strength	Torque meter DBC
Subjective fatigue	Borg Scale 0-10
Pain	Borg Scale 0-10
Activity limitation	
Physical activities	Roland Morris Questionnaire
Activity limitation and participation restriction	
Physical activities	Oswestry Questionnaire
Physical activities and health	SF-36
Personal factors	
Self-efficacy beliefs	Self-Efficacy Scale
Beliefs of consequences of back pain	Back Beliefs Questionnaire

5 RESULTS

5.1 RELIABILITY (STUDY I, IV, V)

Results of reliability are shown in Table 4. In addition, mean values have been used in the reliability analyses, partly mean values of the right and the left recordings, and partly mean values of all four recording sites.

Reliability for the *MVC* (Nm/kg) was high and similar for patients and healthy subjects. Patients were 6% stronger ($p=0.04$) on the second test, while, for healthy subjects, there was no significant difference between the six tests. For the *initial median frequency* and the *slope*, the ICC:s were somewhat higher for the patients than healthy subjects. *Recovery half-time* had low reliability (ICC<0.4) for patients as well as for healthy subjects.

5.2 INFLUENCE OF INTERELECTRODE DISTANCE AND FORCE LEVEL (STUDY III)

Regarding healthy subjects, an increase in interelectrode distance from 2 to 4 cm caused a significant ($p<0.001$) decrease by about 8% in *initial median frequency*. An increase in force level from 40 to 80% MVC caused a significant ($p=0.003$) decrease in initial median frequency of about 10% (Fig. 5).

The *slope* (Hz/s) was not significantly ($p=0.209$) affected by an increase in interelectrode distance from 2 to 4 cm. However, the slope became significantly ($p=0.002$) and strongly (240%) more steep by an increase in force level from 40 to 80% MVC (Fig. 5).

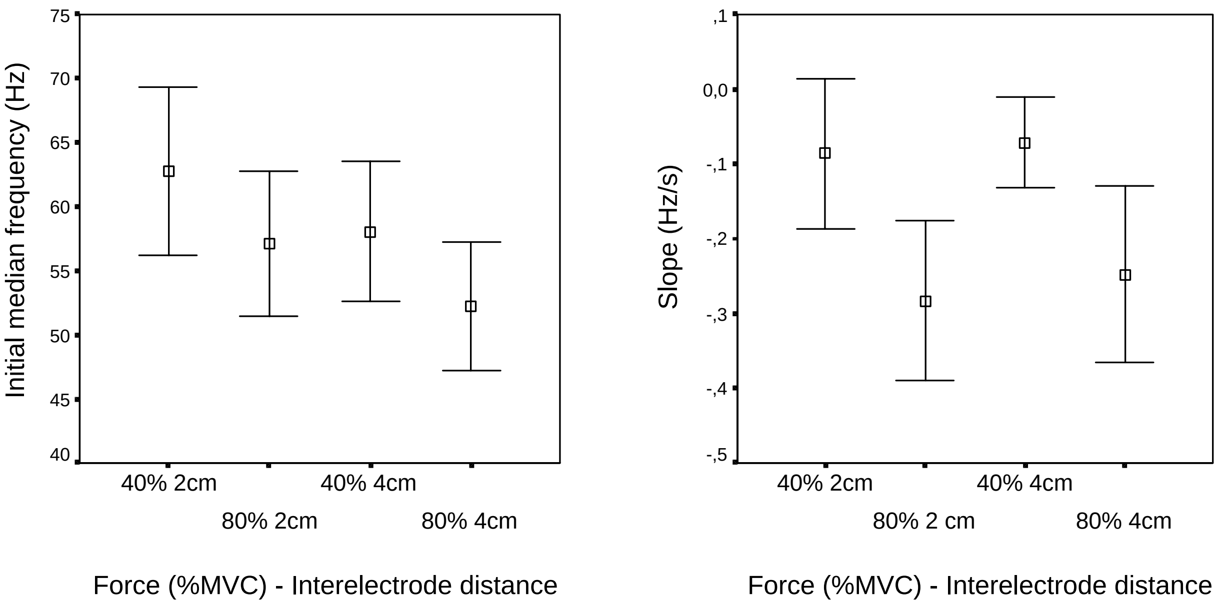

Figure 5. The effect of changing force level and interelectrode distance. Force level is shown in percent of maximal voluntary contraction (MVC). Values are means of the four electrode sites with 95% confidence intervals (n=12).

Table 4. Results of reliability tests for *patients with low-back pain* and *healthy subjects* showing mean values, standard error of measurement S_w and intraclass correlation coefficients *ICC* for maximal voluntary contraction (MVC) torque, initial median frequency f_i and slope. For patients, two measurements were made on two different days. For healthy subjects six measurements were made, twice a day on three different days. The reliability was calculated for each recording separately, for mean values of bilateral recordings, and for mean values of all four recording sites.

Variable	Mean value	Separate recording sites		Mean values of right and left recording		Mean values of four recording sites	
Patients		S_w	ICC [i]	S_w	ICC [i]	S_w	ICC [i]
MVC							
Nm	128	12.3	0.93				
Nm/kg	2.0	0.17	0.93				
f_i (Hz)							
L1 right	54.5	3.4	0.87	3.4	0.86		
L1 left	53.3	3.9	0.80			3.4	0.88
L5 right	61.8	4.3	0.89	4.7	0.86		
L5 left	60.7	6.0	0.78				
Slope (%/s)							
L1 right	-0.22	0.16	0.53	0.16	0.54		
L1 left	-0.20	0.19	0.45			0.16	0.66
L5 right	-0.29	0.19	0.71	0.19	0.70		
L5 left	-0.19	0.23	0.55				
Healthy subjects							
MVC							
Nm	174	18.6	0.93				
Nm/kg	2.6	0.24	0.89				
f_i (Hz)							
L1 right	53.6	5.5	0.41	4.6	0.48		
L1 left	54.4	5.3	0.51			3.4	0.65
L5 right	53.3	4.4	0.64	4.0	0.70		
L5 left	53.2	4.8	0.70				
Slope (%/s)							
L1 right	–0.36	0.27	0.21	0.22	0.35		
L1 left	–0.46	0.20	0.45			0.18	0.32
L5 right	–0.58	0.20	0.46	0.22	0.27		
L5 left	–0.58	0.27	0.04				

[i] ICC 1.1 = BMS-WMS / BMS + (k-1)WMS (For definitions of variances see methods section).

Effects due to possible variation in interelectrode distance should have been negligible, according to present results. Fluctuations in torque level during the test were visually estimated to be about ±10 Nm, somewhat varying between subjects. Based on the difference in the initial median frequency between 40% and 80% MVC, the influence on the initial median frequency from the torque fluctuations was estimated to be about ±1 Hz. For the slope, a similar calculation resulted in an influence from torque fluctuations on the slope of about ±0.03 Hz/s.

5.3 VALIDITY (STUDY V)

5.3.1 Patient characteristics

5.3.1.1 Low-back pain

The low-back pain on the day of the test was moderate for most patients. Median SF-36 Bodily Pain was somewhat higher than for a normal population. The low-back pain during the last four weeks was, for the majority of the patients, easy to moderate. Disturbance of work due to pain was none at all to little for 63% of the patients, and moderate to high for 37%.

Before start of the test, median Borg rating of lumbar pain was 0.5 (quartiles 0-1.5). At the end of the fatiguing contraction median rating was 2, i.e. ”weak” (quartiles 1-4). Median Borg rating remained at 2 (quartiles 0.5-4) during the recovery contractions.

5.3.1.2 Health-related factors

SF-36 Reported Health Transition, i.e. the general health compared to one year ago, was somewhat or much better for 21 patients, about the same for 22 patients, and somewhat or much worse for 14 patients. The patients´ activity limitations were rather low as measured with Roland Morris (median 5) and Oswestry (median 16%). For SF-36 the results are here given as a percentage of the median value of the healthy Swedish norm [157]; Physical Functioning 84%, Role Physical 75%, Bodily Pain 62%, General Health 94%, Vitality 87%, Social Functioning 88%, Role Emotional 100%, and Mental Health 91%; the scores for personal factors were for self-efficacy 75% and for back beliefs 67% of maximum possible score (Study V, Table 2). The men scored significantly better than the women in Physical Functioning ($p=0.008$), self-efficacy ($p<0.001$) and Oswestry standing ($p=0.028$).

5.3.2 Differences patients – healthy subjects (Study V)

5.3.2.1 Maximal voluntary contraction

MVC was significantly ($p<0.001$) lower for male and female patients compared to the healthy subjects (Table 5) Men had significantly higher MVC than women, for patients ($p=0.002$) as well as for healthy subjects ($p<0.001$). Considering the three trials of MVC with one minute rest in between, from the first to the second trial patients ($p<0.001$) and healthy subjects ($p=0.019$) increased their strength significantly. However only the patients increased their strength significantly ($p=0.017$) from the second to the third trial, while the strength of the healthy subjects levelled out.

5.3.2.2 EMG initial median frequency

The patients had significantly ($p<0.001$) higher initial median frequency at L5 than at L1 level. This differed significantly ($p=0.013$) from the healthy subjects. There was no significant gender difference neither for patients ($p=0.873$) nor healthy subjects ($p=0.947$) (Table 5). No significant right-left differences were found for patients ($p=0.140$), nor for healthy subjects ($p=0.892$).

5.3.2.3 EMG Slope

Patients had significantly flatter slope (%/s) than healthy subjects ($p=0.011$). However, considering gender differences, female patients had significantly flatter slope than male patients ($p=0.005$) and healthy females ($p=0.002$); there was no significant difference between male patients and healthy males ($p=0.444$) (Table 5). No right-left differences were found for patients ($p=0.243$) nor for healthy subjects ($p=0.062$). The normalised slope (%/s) was similar at L1 and L5 level for patients ($p=0.119$); however, for the slope in Hz/s, the L5 level was steeper ($p=0.005$).

The relative number of significantly negative slopes obtained in individual recording sites was for patients 50% and for healthy subjects 70%.

Table 5. Maximal voluntary contraction (MVC) torque and EMG variables for *patients with long-term low-back pain* and *healthy subjects*. Mean values and standard deviations are shown for L1 and L5 level for patients and healthy subjects, men and women. There were no significant right-left side differences. Initial median frequency = f_i.

Variable	**Patients**		**Healthy subjects**	
	Men (n=27)	Women (n=30)	Men (n=27)	Women (n=26)
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
MVC *(Nm/kg)*	2.3 (0.8) [b]	1.7 (0.6) [b]	3.5 (0.9) [b]	2.5 (0.7) [b]
f_i *(Hz)*				
L1 level	51.5 (8.4) [c]	53.5 (9.6) [c]	51.7 (9.6)	53.1 (7.6)
L5 level	60.0 (9.5) [a c]	58.7 (11.0) [a c]	51.5 (9.9) [a]	51.2 (8.1) [a]
Slope *(%/s)*				
L1 level	-0.333 (0.270) [b c]	-0.181 (0.200) [a b]	-0.390 (0.289) [c]	-0.339 (0.197) [a c]
L5 level	-0.430 (0.374) [b c]	-0.167 (0.274) [a b]	-0.491 (0.276) [c]	-0.384 (0.213) [a c]
Slope *(Hz/s)*				
L1 level	-0.171 (0.143) [b c]	-0.100 (0.111) [a b]	-0.216 (0.166) [c]	-0.186 (0.115) [a c]
L5 level	-0.265 (0.235) [b c]	-0.106 (0.164) [a b]	-0.269 (0.178) [c]	-0.202 (0.118) [a c]

[a] = significant differences between patients and healthy subjects ($p<0.05$)
[b] = significant differences between men and women ($p<0.05$)
[c] = significant differences between lumbar level L1 and L5 ($p<0.05$)

5.3.2.4 EMG recovery half-time

The recovery half-time calculated on group mean values of all patients or all healthy subjects, respectively, were longer for patients at all recording sites. The recovery half-time were for patients 74-96 s and for healthy subjects 32-39 s. The ratio in half-time between patients and healthy subjects was thus about 2.5. The coefficients of determination R^2, i.e. the explanatory values, were excellent (≥0.97). The pattern of the fatigue and recovery phase is shown in Fig. 6.

The relative number of exponential-like recovery results in individual recordings was for patients 63% and for healthy subjects 69%.

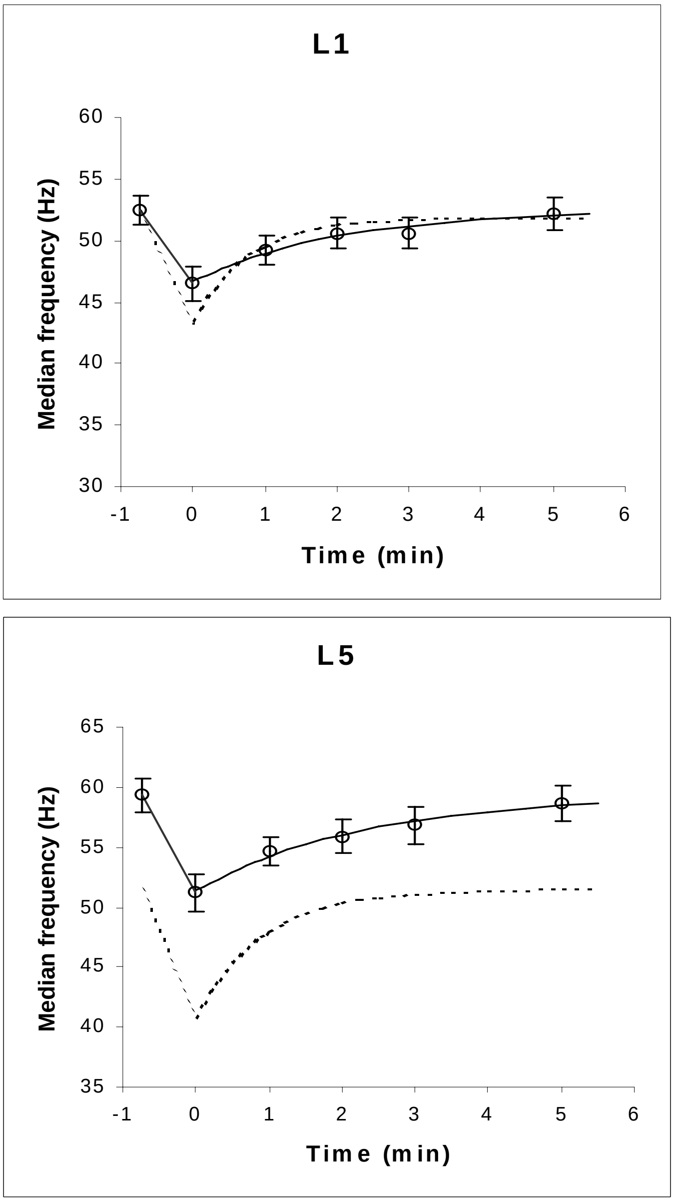

Figure 6. The fatigue and the recovery process at L1 and L5 (means of right and left recordings). Mean values and standard errors are shown for the patients with the fitted exponential curve as a full line. The fatigue phase and the exponential fitted curve to data of the healthy subjects are shown as a dotted line.

5.3.2.5 Discrimination between patients and healthy subjects

Independent variables in backward stepwise logistic regression were MVC (Nm/kg), initial median frequency at L1 and L5, slope (%/s) at L1 and L5, and recovery half-time at L1 and L5. To avoid strongly correlating variables, the mean value of the right and the left side was used. Significant variables remaining at step four in order of importance according to the Wald statistic [123] were MVC, initial median frequency at L5, initial median frequency at L1 and recovery half-time at L1. The sensitivity/specificity was 86/78%, (cut-off value 0.5).

The most significant variables were MVC and initial median frequency at L5. If only these two variables were used, however, the sensitivity/specificity decreased to 75/75%. When the regression was made not including MVC, i.e. with only the EMG variables, significant variables remaining at step three were initial median frequency at L5, slope at L5, and initial median frequency at L1. The sensitivity/specificity was 75/80%. If instead only MVC was used the result was 77/69%. If only initial median frequency at L1 and L5, or the slope at L1 and L5 were used, the sensitivity was 67% with somewhat lower specificity.

5.3.2.6 EMG fatigue and recovery versus health-related factors in patients

The number of patients and healthy subjects in the different groups classified according to EMG fatigue and recovery are shown in Table 6. Significantly more patients than healthy subjects had absent EMG fatigue (p=0.025), but there was no significant difference in the occurrence of exponential-like recovery (p>0.05).

Table 6. Number of patients and healthy subjects with EMG fatigue, absent fatigue, exponential-like recovery or not exponential-like recovery for EMG median frequency. Expected frequencies under the null hypothesis are shown in parenthesis.

	Fatigue	Absent fatigue	Total
Patients	**24** (30)	**33** (27)	57
Healthy	**35** (29)	**20** (26)	55
Total	59	53	112

Chi-square 5.2 p=0.025

	Exponential-like recovery	Not exponential-like recovery	Total
Patients	**32** (36)	**25** (21)	57
Healthy	**38** (34)	**17** (21)	55
Total	70	42	112

Chi-square 2.0 p>0.05

Furthermore we combined fatigue and recovery making a classification into four groups according to Dedering et al. [33]. The four groups are shown in Table 7 for patients and healthy subjects. The majority of the healthy subjects had EMG fatigue and exponential-like recovery, which would thus be considered normal; with absent EMG fatigue, the recovery was nevertheless exponential-like in most cases. There was no significant difference from the expected frequencies under the null hypothesis (p>0.05). For patients, there was a significant probability that, having absent EMG fatigue, the recovery would be not exponential-like (p=0.025).

Table 7. Number of patients and healthy subjects in the four categories according to the occurrence of EMG fatigue or absent fatigue, exponential-like recovery or not exponential-like recovery in EMG median frequency. Expected frequencies under the null hypothesis are shown in parenthesis.

Patients	Exponential-like recovery	Not exponential-like recovery	Total
Fatigue	**18** (13.5)	**6** (10.5)	24
Non-fatigue	**14** (18.5)	**19** (14.5)	33
Total	32	25	57

Chi-square 6.0 p=0.025

Healthy subjects	Exponential-like recovery	Not exponential-like recovery	Total
Fatigue	**26** (24)	**9** (11)	35
Non-fatigue	**12** (14)	**8** (6)	20
Total	38	17	55

Chi-square 1.2 p>0.05

Patients with absent fatigue *or* not exponential-like recovery *or* the combination of absent EMG fatigue and not exponential-like recovery scored worse on several items of the questionnaires measuring activity limitations, participation restrictions and self-efficacy, e.g. Roland Morris, Oswestry, Physical Functioning, Bodily Pain and self-efficacy (Table 8).

No significant difference was seen between the groups for Borg ratings of pain before and at the end of the test. Neither was there any significant difference between the classification groups concerning the number of years a patient had suffered from back pain (the patients with absent EMG fatigue had nearly significantly longer pain duration; p=0.06). There were no significant differences between any of the groups regarding SF-36 Role Physical, General Health, Vitality, Social Functioning, Role Emotional, Mental Health, neither for back beliefs.

Table 8. Significant differences in scores from questionnaires according to three different combinations of grouping the patients. *Fatigue:* Significantly negative EMG slopes on 3 or 4 recording sites. *Absent fatigue:* Not significantly negative slopes on 2, 3 or 4 recording sites. *Exponential-like recovery:* The exponential model could be fitted to individual input data f_e, f_1, f_2, f_3, f_5, f_i of recovery on 3 or 4 recording sites. *Not exponential-like recovery:* The exponential model could not be fitted to input data on 2, 3 or 4 recording sites. Only questionnaires and items with significant differences ($p \leq 0.05$) are shown (Roland Morris Back Pain Questionnarie, Oswestry Low Back Pain Disability Questionnarie, SF-36 = Short Form-36 Health Survey, Self-Efficacy Scale).

Questionnaire	Fatigue	Recovery	Fatigue and recovery
	P-value [1]	P-value [2]	P-value [3]
Roland Morris score	0.020		0.027
Oswestry total score	0.006	0.052	0.002
Personal care	0.008	0.013	0.005
Lifting	0.005	0.054	0.012
Sitting			0.021
Travelling			0.013
SF-36			
Physical functioning (PF)	0.014		0.020
Part items (PF)			
Intense activities	0.013		
Bend down or kneel	0.012		0.007
Take a bath or dress	0.046		
Walk more than 2 km		0.028	
Bodily pain (BP)	0.052		
Part items (BP)			
Pain during the last 4 weeks	0.046		
Health compared to one year ago		0.003	0.013
Self Efficacy total score	0.034		
Carry bags (2x4-5 kg)	0.040	0.013	0.035
Work in a forward bent position	0.034		
Standing (in line)		0.024	

[1] A p-value ≤0.05 means that patients having absent EMG fatigue scored significantly worse than other patients.

[2] A p-value ≤0.05 means that patients having not exponential-like recovery scored significantly worse than other patients.

[3] A p-value ≤0.05 means that patients with the combination of absent EMG fatigue and not exponential-likerecovery scored significantly worse than other patients.

5.4 CORRELATIONS (STUDY II, V)

Higher MVC was strongly correlated to a more negative slope ($r \approx -0.72$) for patients but not for healthy subjects ($r \approx -0.41$). There was hardly any correlation between slope and Borg ratings of pain for patients ($r_s=0.21$) or slope and Borg ratings of fatigue for healthy subjects ($r_s=0.02$).

Significant correlation ($p<0.01$) between activity limitation and participation, pain, self-efficacy, slope, and MVC were found; Roland Morris, Oswestry, Physical Functioning and self-efficacy correlated moderately ($r=0.50$-0.60) to pain today, pain last month and pain disturb work. There were low correlation ($r_s \approx 0.4$) between slope versus activity limitation and pain.

The number of years a patient had suffered from back pain had hardly any correlation with the questionnaires ($r_s<0.24$), and low correlation with MVC/kg ($r=0.38$, $p<0.01$), slope ($r=0.29$, $p>0.05$) and initial median frequency ($r=0.26$).

6 DISCUSSION

The most important findings concerning the validity of the present test are that patients with long term low-back pain and back-healthy subjects could be correctly classified in about 80% of the cases, and that subjective assessments of health-related factors were related to EMG fatigue and recovery.

6.1 SUBJECTS

The present patient group seems to be a sample representing a common group of people with low-back pain; having recurrent long-term non-specific low-back pain, seeking health care for their pain, and working in spite of pain. Five different questionnaires were used to describe various aspects of health. According to the SF-36, the health of the patients seemed to be more limited in physical than other health-related factors (General Health, Vitality, Social Functioning, Role Emotional, Mental Health), when compared to a normal population. Using inclusion- and exclusion criteria, we wanted to exclude patients with nerve root symptoms from the lower discs, and we wanted to include patients with long pain duration, at least 6 months in the previous year. It turned out that 50% of the patients had had a pain duration between 4-16 years, similar for men and women. The patients were tested when their pain had decreased somewhat, and all patients were able to perform the 45 s contraction. Our aim was to have about the same proportion of men and women for patients and for healthy subjects, since there is no gender difference in the prevalence of low-back pain [80]. We did not get as many patients on sick-leave as we had expected. This might be due to a selection of patients seeking care at the physiotherapy clinics involved. However, the large majority of people with low-back pain continue working [175]. In retrospect, it might even be an advantage with a more homogenous group of working people in this study. As a complement, in a future study, patients on sick-leave could be studied. The healthy subjects were tested before the start of the patient study. A drawback due to this is that the healthy subjects were not given any questionnaires.

The statistical power of a hypothesis test depends on the sample size, the size of the detected difference, e.g. between patients and healthy subjects, and the standard deviation [3]. In retrospect power calculations were made. Obtained power was for in initial median frequency and MVC 1.00 and for the slope 0.7. Thus, a difference of about 10 Hz in initial median frequency and 1.0 Nm/kg could be considered a clinically relevant difference between patients and healthy subjects. To reach a power of 0.8 for the shown slope difference of about 0.15 %/s, about 75 subjects would have been needed in each group. Recovery half-time was not normally distributed and power analysis was therefore not made on that variable.

6.2 MVC-BASED PROTOCOL

Since it has been shown previously that patients with low-back pain were better identified at 80% of MVC [124,140], we wanted to be able to test at this force level with force feed-back. Therefore we chose the DBC test and training device, where the subjects were seated in a fixed reproducible position. To identify the target force, the subjects had to perform an MVC. Our subjects were verbally encouraged to do their best. Verbal encouragement has been shown to increase biceps strength by 5% in healthy subjects, with no simultaneous change in median frequency [102]. The subjects had three trials of MVC and we chose to take the mean of the two highest values, to obtain a more steady and fair value than taking the highest value which is otherwise common. The mean or median value out of three trials has also been used previously [58,126,149].

EMG fatigue tests can be based on the MVC, as in our protocol, or on the weight of the trunk, like in Sørensens test. There are advantages and disadvantages with both methods. Using the MVC based protocols, an advantage is the possibility to test at different contraction levels. Motivation, pain or fear of pain will influence the MVC as well as the endurance time to failure point. To avoid the influence of motivation in tests reaching exhaustion, a fixed test time has been used [10]. The problem will then be ceiling effects, i.e. many subjects reach the time limit. However, if EMG is simultaneously recorded the median frequency slope could be calculated for a fixed contraction time [90], or for a contraction time interrupted at a certain subjective assessment of back muscle fatigue [34]. However, the objectivity of EMG can be discussed for all tests where motivation is involved in the performance.

In order to avoid the need to measure MVC, different methods have been tried previously. The load level has been calculated with a formula using body mass, height, sex and age to obtain a submaximal dynamic load [67]. Whether anthropometric measures could predict back extensor MVC has also been studied. It was found that shoulder, hip and thigh circumference [124] and body mass [88] could predict MVC. We made a similar study including 50 men and women, but we found no such correlations [44] and therefore continued to use MVC.

As it is quite strenuous to maintain an extension contraction at 80% MVC for 45 s, our ambition was to look for a possibility to shorten the contraction time (Study II). However, the slopes for 20 s, 30 s and 45 s showed the same mean value, but an increasing between-subjects variability as the contraction time became shorter, similarly to another study [172]. This would probably have a negative effect in the usefulness of the slope in discriminating between patients with low-back pain and healthy subjects. Better reliability for longer slopes has also been shown by Dedering et al. [36]. We therefore chose to use a 45 s contraction also for the patients.

6.3 SUBJECTIVE RATINGS

The healthy subjects were instructed to rate fatigue, or rather effort, in the lumbar back during the contraction. This measure turned out to be not as useful (Study II) as previously shown for the Sørensens test [34]. The test position might influence the correlation between ratings of fatigue and slope, since low correlations were also found for a test in standing position [35]. Since some of the healthy subjects expressed difficulties in rating the localized low-back fatigue in this test situation, we decided to let the patients rate only low-back pain. There were low correlations between Borg ratings of low-back pain versus EMG variables and MVC. These ratings in the present test could therefore be questioned. However, it seems important to know the degree of back pain of patients performing a test requiring such a high effort.

6.4 EMG

The lumbar muscles consist of several layers of different muscles, with short and long muscle fibers in different directions. We used four pairs of electrodes, placed bilaterally on the medial lumbar muscles, i.e. longissimus thoracis at L1 and multifidus at L5, according to Roy et al. [30,140]. However, in view of the complexity of the lumbar extensor muscles we prefer to describe our electrode sites by lumbar level instead of by specific muscles.

The magnitude of decrease in median frequency with a larger interelectrode distance is in accordance with a model based on Lindström´s theory [81] (Study III). However, the model also showed that the median frequency could increase as well as decrease. This is also what we noticed in our measured individual data. In conclusion, this spread in shift of median frequency with a change in interelectrode distance is likely to be connected to randomlike variations in the shape of the power spectra and to variations in conduction velocity.

The sampling frequency should be at least twice the bandwidth to prevent aliasing [5]. When checking the bandwidth of the input electronics it was, in retrospect, found to be 10-800 Hz. Our power spectra were in general centered roughly around 50 Hz, and decreased to very low values already at frequencies about 200-250 Hz. The area of the power spectrum in the range 200-500 Hz was typically about 1-2% of the area in the range 0-200 Hz. It follows that the possible contribution to the spectral area in the 200-500 Hz range from aliasing should not exceed 1-2% of the total power spectrum area. Therefore, the *maximum possible* error in median frequency due to aliasing should be of the same order of magnitude, i.e. at most about 1 Hz. Moreover, the shape and appearance of the power spectra did not indicate the presence of any aliasing effects. In addition, we made some trials with registrations using sampling frequency 1000 Hz and 2000 Hz alternatively, and found the power spectra to be similar and with no significant differences in median or mean frequency.

6.5 FORCE LEVEL

With a change from 40% to 80% MVC a change in median frequency was expected, suggested to be due to recruitment of more type II motor units at higher force levels [32,151]. Consistently, a change in contraction force from 40% to 80% MVC caused a decrease in initial median frequency of about 10%, in agreement with the argument that the type II fibers of the back muscles are of smaller size than the type I fibers [91,140] (Study III). Similar decrease with force at L1 and L5 have also been reported by others for healthy subjects as well as for low-back pain patients [35,78,141]. Mannion and Dolan [91] found a similar decrease for the lumbar muscles (L3) for force levels increasing from 40% to 80% MVC. In the thoracic region (Th10) they found instead an increase in median frequency and therefore suggest, that the fibers recruited at higher force level are smaller in the lumbar region but larger in the thoracic region. However, in a previous study by the same authors [40] no change in median frequency was found like in other studies [138,145,180]. Varying electrode positions, posture and force levels as well as the complexity of fiber types in the back muscles might cause these conflicting results.

The decrease in median frequency during the 45 s contraction was significantly more rapid at the higher force level. A proposed explanation for this is that the median frequency decrease is mainly due to a decrease in conduction velocity, which, in turn, mainly is due to the accumulation of lactate in muscle and blood [32]. Since the type II fibers are glycolytic, lactate will accumulate when these fibers are active, which increasingly will be the case with higher force levels. Thus, the median frequency slope should become steeper with higher muscle force. This has been confirmed in a number of studies [35,40,78,140,141,172].

The decrease in median frequency during a contraction depends on the type of muscle, the contraction time and the exerted percent MVC [5]. One may think that the effort to perform an 80% MVC contraction for 45 seconds should be sufficient to produce EMG fatigue in the lumbar muscles. However, the median frequency decrease was only about 10 Hz for healthy subjects (Study II) and more than twice as large for the Sørensens test [34]. Therefore it might be speculated that a contraction at a lower intensity (percent MVC), but performed for a longer time, could be ”more fatiguing” in terms of EMG median frequency slope.

6.6 EXPONENTIAL MODEL OF RECOVERY

The EMG recovery of the back muscles has not previously been studied using several repeated measures during the recovery period. With this type of protocol a statistical analysis using non-linear regression is possible, taking advantage of the exponential recovery process.

In order to measure recovery with EMG the rest period has to be interrupted with short muscle contractions. There has to be a balance in the test protocol between the number of recordings wanted for a good estimate of the recovery, and not interfering too much with the repose in the recovery period. As mentioned before, in previous studies on back muscles the recovery was measured only once, after 1 min [129,142]. Statistical methods commonly used to get an estimate of the time required for recovery are ANOVA and t-test, where the initial variable value is compared to the values obtained during recovery. The result will indicate either no recovery or full recovery, according to whether there is or is not a statistically significant difference. Using these statistical methods, the significance of mean differences, however, will depend on the number of subjects involved. As a consequence, the time to recovery, if defined in this way, may change systematically if the number of subjects is changed. By contrast, the non-linear regression makes use of all recovery data simultaneously and can be used on group mean data as well as on individual data. A time for full recovery cannot be unambiguously defined using an exponential time dependence model, but we may define a recovery half-time. Provided that an exponential recovery process is an appropriate model, the recovery half-time, determined in this way, should not change systematically with an increasing number of subjects; it should however be better determined.

Median frequency mean data showed a clear exponential-like course during recovery (Study IV). Van der Hoeven et al. [170] investigated the recovery of the biceps brachii after one minute isometric MVC. From analysis of mean data, they report the recovery half-time for the mean power frequency to be 84 s, which is somewhat longer than our half-time of about 35 s. Our half-time for patients (group mean data) were about 2.5 times longer than for healthy subjects. Using group mean values when analysing recovery half-time seems useful when the purpose is to know the rate of recovery. Recovery half-times from calculations on individual data turned out to have large variability. In classifying the patients, recovery half-time was used only to see if the recovery data were exponential-like.

With our test protocol we measured until 5 min into the recovery period, which seemed to be enough since 70% of the half-times were less than 60 s and only 3% were longer than 300 s for healthy subjects. For patients the figures were 55% and 11%, respectively. One might expect that half-times around the median values, i.e. 30-90 s, should be better determined, but the coefficient of determination R^2 had no correlation with recovery half-time. However, half-times from non-fatigue recordings had generally lower R^2 values (Study IV,V).

6.7 RELIABILITY

The reliability for EMG variables was somewhat better for the patients than for the healthy subjects, although the patients were 6% stronger on the second test (Study I,V). A recent article report similar reliability for patients with low-back pain and healthy subjects, and, similar to our results, an increase in MVC for the patients from the first to the second test session [79]. One reason for our higher reliability for patients could be that, in the patient study, we made a template of the electrode placement at the first test occasion. The number of subjects multiplied by the number of measurements is recommended to be at least 25 in reliability studies [22]. The healthy subjects were tested six times (Study I). However, since it was easier for patients to come to the laboratory twice than three or more times in a short time period, we instead increased the number of patients. The lumbar pain could also have changed in a longer time period. As for now the rated pain of the patients were the same ± 1 score on the Borg scale at the two test occasions.

To increase reliability in EMG measurements, average values of recording sites or test sessions could be used [73,79]. Statistically, mean values should be more reliable than single values. For our data, reliability on mean values of right/left recordings and of all recording sites, respectively, showed similar ICC:s and somewhat lower standard error of measurements for mean values compared to the results for each recording site (Table 4). Since no right-left differences for the EMG variables have been shown, neither for patients nor for healthy subjects, mean values of bilateral recordings could be used. Using mean values of all four recording sites would, however, make important differences between L1 and L5 level disappear, unless an overall estimate of lumbar muscle fatigue is desired.

The MVC torque showed excellent reliability in between-days measurements for patients and healthy subjects. This type of measurement has also been used in clinical evaluations for a long time. When the subjects maintained 80% MVC torque during the fatigue contraction they continuously observed a torque meter. From our results on the median frequency by a change in force level from 40% to 80% MVC, we could conclude that torque fluctuations during the fatigue phase should have had minor influence on the standard error of measurement (Study III). However, it is important that the patient is carefully instructed about the test procedure and is given the opportunity to practise maintaining torque level.

Recovery half-time based on individual median frequencies was highly variable as a measure of EMG recovery, possibly because the non-linear regression curve was obtained by fit to only six median frequency data points during the recovery phase (Study IV). This may be compared with the fatigue phase, where the linear regression line was fitted to 45 data points. Due to the rapid recovery at the beginning of the rest period, a measurement after 30 s might have facilitated the non-linear regression. However, an extra 5 s contraction after 30 s would interfere with the recovery process itself.

For individual evaluation in a clinic the initial median frequency could be used, though there still remain some questions about its validity. The slope alone had not sufficient reliability for individual follow-up measurements. Neither had the recovery half-time, with the present protocol. Larivière et al. [79] make a similar conclusion stating that EMG indices should be limited to group tendencies, while Koumantakis et al. [73] are more positive to the clinical applicability provided changes of therapy exceed $1.96*S_{diff}$. However, in the present study, when classifying patients according to the presence of significant EMG fatigue and exponential-like recovery, slope and recovery half-time turned out to be very useful variables. Also, the slope and the recovery half-time can be useful in combination with the initial median frequency and the MVC in a logistic regression.

6.8 COORDINATION OF THE LUMBAR MUSCLES

Detailed investigation of individual recordings showed the occurrence of not significantly negative slopes during contraction (Study IV). An interesting feature was that these slopes were randomly distributed on *one, two or three* recording sites in the majority (49%) of the healthy subjects. In these subjects 42% had *significantly negative* slopes on *all four* recording sites, while 9% had *non*-significant slopes on *all four* sites. Since so many healthy subjects could have an occasional non-significant slope, we decided that when we made the classification into a fatigue- and a non-fatigue group, we would classify subjects with only *one* occasional non-significant slope into the fatigue group. The same phenomenon was seen among the patients; here however, the proportion non-significant slopes were higher (Study V). A classification based on whether the individual slope was significantly negative seems, to our knowledge, not to have been made before; in the literature the description is usually in terms of mean slope values and standard deviations. However, it gave new information. It seems possible that with a test in a seated position, isometrically pressing backwards, muscle coordination may actually vary for different subjects and for the same subject at different measurements. In fact, the central nervous system can vary the activation within a muscle group during sustained contraction [45]. This may indicate different coordination strategies for the lumbar muscles during the fatigue test in a seated position.

We also questioned if the occurrence of not significantly negative slopes could be due to the subject not performing a “true” MVC. This is of course difficult to check, but we do not have reason to believe this to be the case for healthy subjects. Also, it hardly explains the random occurrence of not significantly negative slopes on *some*, but not *all* recording sites.

Similarly to the fatigue phase, in individual recovery data a random appearance of non-exponential-like recovery was found, and this appeared to a larger extent among the patients.

Analysing the six measurements for the healthy subjects, it could be noticed that, in all subjects except one, a few random not exponential-like recordings could be found at different recording sites (Study IV,V).

6.9 VALIDITY

6.9.1 Discrimination between patients and healthy subjects

A good diagnostic test should have high sensitivity, i.e. ability to correctly classify patients as patients, as well as high specificity, i.e. ability to correctly classify healthy as healthy [100]. The ability of our test to classify the 112 subjects in patients or healthy was relatively good. The highest sensitivity (86%) was obtained when entering the EMG variables initial median frequency, slope and recovery half-time together with MVC. Forward and backward stepwise regression gave the same result. The strongest predictor was MVC, but adding EMG variables improved both the sensitivity and the specificity. However, EMG variables without MVC had similar sensitivity (75%) as using only MVC. Previous studies, however, have shown good discriminative validity of EMG variables, e.g. slope, initial median frequency, and recovery after 1 and 2 min, with a sensitivity of about 85-100% without MVC [9,70,129,141]. In the present study, the strongest predictor among the EMG variables was by far the initial median frequency at L5. We hesitated to use individual recovery half-time because of the low reliability. Logistic regression without entering half-time resulted in a sensitivity of 83%, i.e. only one patient less correctly classified. In the logistic regression we used the mean of the right and the left side of the EMG variables to decrease the number of correlated variables. Using mean values of all four recording sites gave, however, a lower discriminating validity.

6.9.2 Maximal voluntary contraction

Both male and female patients showed significantly lower strength than the healthy subjects (Study V). A possible first guess as regards the reason for the patients´ lower strength, is that they were unable or unwilling to produce a ”real” MVC, thus performing less than 80% MVC on the test. Before doing the test, the patients trained keeping a submaximal force in the test unit, but they did not practise MVC in order not to tire themselves. The electrodes were then attached in a prone position to give the patient some rest. The mean MVC increased significantly ($p<0.001$) by 14% during the three trials, indicating a learning effect. However, MVC only increased with 6% between days, as mentioned. More practice of MVC performance seems indicated. It could be made in connection to practicing the submaximal force provided a longer rest before the test is given. A second reason for a low MVC could have been pain. Gender, cross-sectional muscle area and pain on exertion has been shown to be powerful predictors of isokinetic back muscle strength [69]. This was, however, an isometric test and our patient group had not much pain before or during the test. Moreover, the correlation between MVC and pain rated at the start of the test was also very low. However, fear of pain can be as disabling as pain itself [112] and this variable might always play a role. Crombez et al. [29] have shown that in patients with long-term back pain the most consistent predictors of flexion and extension peak torque were pain related fear measures; *expected* pain increase, not *experienced* pain increase. However, the lower MVC of the patients compared to the healthy subjects in the present study agrees well with results from a number of previous studies [53,66,108,127,141].

6.9.3 EMG differences between patients and healthy subjects

Two models of explanation (1) and (2) will be presented here to discuss the EMG differences between the patients and the healthy subjects in Study V, since results of EMG changes depend on the exerted force and thus on the performed MVC.

(1) If the patients in our study really had performed a ”true” MVC, a possible reason for the flatter slopes in patients when compared to healthy subjects, accentuated for the women, might be deconditioning of the lumbar muscles due to pain and decreased activity. A type II fiber atrophy is then often seen [117,154], which would result in a lower back muscle strength, also observed in our patients. A presence of type II fiber atrophy in the patients would explain the observed flatter slopes, due to the necessary recruitment of the fatigue resistant type I fibers. These fibers are also, as stated in the background, larger than the type II fibers in the lumbar muscles and should thus give higher median frequencies. This might explain the higher initial median frequency at L5 found for patients. High type I fiber activation corresponds with previous research reporting an adaptive response in multifidus due to an increased role in stabilizing the lumbar spine in patients with long-term low-back pain [154]. A decrease in initial median frequency has also been shown after dynamic back muscle training in patients with back pain [108], which might indicate more activation of type II fibers. An increase in the size of the type II fibers has indeed also been shown after intensive strength training of the back muscles [134], while no major changes in fiber size were found after training programs which were not concentrated on back muscle strength [76]. Furthermore, fatty infiltration of the paraspinal muscles is considered a sign of muscle degeneration, which can be found also in pain-free individuals, but to a larger degree in persons with low-back pain [127]. These changes might also have influenced the EMG spectral variables. However, our results are not in accordance with Mannion et al. [95], who report alterations in fiber size into more fatigable (glucolytic type IIX) over the long term in patients with low-back pain.

(2) If the patients did not perform a “true” MVC, due to for example fear of pain, and thus performed lower than 80% MVC during the fatigue test, they should have activated mostly type I fibers. Therefore, the higher initial median frequency on L5 for patients compared to healthy again seems reasonable. Furthermore, our results showing lower initial median frequency and steeper slope at a higher contraction level, indicate that healthy subjects activate more of their type II fibers at contractions as high as 80% MVC (Study III). A lower than 80% MVC would also explain the flatter slopes seen in the patients compared to the healthy subjects. The male patients had flatter slope than the healthy males, but not significantly, whereas the female patients had significantly flatter slope than the healthy females. It therefore seems probable that the women to a higher degree did not produce a force large enough to activate their type II fibers and thus produce EMG fatigue in their lumbar muscles.

Another argument for the second hypothesis is that the correlation between the observed MVC and slope was high for the patients and low for the healthy subjects. Patients performing a high MVC also had steeper slopes, indicating an ability to activate the type II fibers and possibly less degeneration of these fibers. The MVC of the healthy subjects had low correlation with the slope, but showed variations possibly indicating individual fiber type composition in the lumbar muscles.

There is not more support for one explanation than the other. However, both seem to fit the pattern of observations, and also support the indication that women have more impairment in their lumbar muscles, also explained by the result that women scored worse on some of the physical activities in the SF-36 questionnaire, e.g. for intense and moderate intense activities, lifting and carrying. The men also had significantly higher self-efficacy in physical activities (Study V).

6.9.4 Muscle fatigue and recovery versus health-related factors in patients

In the classification of the patients into four groups, 33% of the patients had absent EMG fatigue as well as not exponential-like recovery according to the classification scheme (Study V; see also Table 7). Among the healthy subjects this occurred for only 15%. It seems very interesting that these patients, where muscle fatigue as well as recovery could be impaired, also scored worse than the other patients in activity limitations, e.g. Roland Morris, Oswestry, SF-36 Physical Functioning, and in self-efficacy (Table 8). Similar results are reported from Dedering et al. [33] who had 9% of their patients with lumbar disc herniation in this group, and these patients scored worse in Oswestry (pain and standing) and SF-36 (Physical Functioning), and in self-efficacy (standing and biking) compared to the other groups. Thus, we found, rather unexpectedly, a connection between activity limitation and the absence of significant slope and exponential-like recovery.

The types of activities for which the patients having absent EMG fatigue and/or not exponential-like recovery scored significantly worse, were activities of daily living which requires endurance of the back muscles, e.g. personal care, lifting, bending down, and carrying bags (Table 8). This EMG result may indicate some possible impairment in the lower back muscles for patients with long-term low-back pain, or perhaps a lower MVC due to fear of pain (corresponding to explanation 1 and 2, respectively). Moreover, the women seemed to have greater problems than the men, and were significantly more limited in for example the SF-36 lifting and carrying bags (p=0.009) and Oswestry standing (p=0.028). In these activities a good function of the lower back muscles is important. However, for the load on the spine, the moment arms of the muscles must also be taken into consideration, and these have been shown to be different for men and women [113,114], which could also have influenced the results. Pain was also higher in the group with absent EMG fatigue. Pain and activity limitation in patients with long-term low-back pain has been shown to be decreased after physical training, and, strangely enough, in combination with either a flatter slope [65] or a steeper slope [94].

However, none of the other health-related factors (Role Physical, General Health, Vitality, Social Functioning, Role Emotional, Mental Health, and back beliefs) differed significantly between the groups. This is in interesting contrast with Mannion et al. [94] who report psychological factors to be highly associated with activity limitation. A plausible explanation might be that only about 50% of the patients in the study sample of Mannion et al. [96] were full time working and about 25% were retired/unemployed/homemaker. In our sample 91% of the patients were full time working. Working might also be the reason why we did not detect any differences between the groups in the Back Beliefs Questionnaire. We found earlier, in connection with translating this questionnaire into Swedish, that patients with low-back pain who were working had similar scores as healthy subjects and significantly higher scores than patients with low-back pain who were on sick-leave.

6.10 RELATED STUDIES CONCERNING SLOPE

In studies using EMG it has previously been shown, in agreement with our present results, that men and women with low-back pain had flatter slope at L5 level than healthy subjects [129]. However, a lack of observed difference in lumbar paraspinal slope between women with low-back pain and healthy women has also been reported [66]. Furthermore, several studies have claimed patients with low-back pain to have steeper slopes than healthy [9,98,140,167]; in these studies the test groups consisted of only 10-27 patients, mostly men. In studies evaluating active rehabilitation, a less steep slope has been reported after training [98,141,164], also in combination with a decrease in pain and increase in activity and participation [65,108]. This is considered to be a positive result, i.e. the muscles are ”less fatigable”. However, the MVC load has, in these studies, been the same before and after rehabilitation. Therefore, it may be suggested that the load relative to strength during the post-test should be less, due to increased strength, which may have led to a flatter slope for that reason. In a recent study though, Mannion et al. report more EMG fatigue (steeper slope) after training [97] and a decrease in activity limitation as well [94]. This is more in accordance with the present findings.

6.11 FURTHER RESEARCH

Based on the findings of this thesis, interesting subjects for future studies would, for example, be

- to study the influence of pain-related fear and self-efficacy on MVC
- to study the effect on the lumbar muscles EMG variables of muscular strength training,
- to study another category of patients, namely, patients on longer sick-leave periods for low-back pain, using EMG frequency variables and health-related factors,
- to study coordination strategies of the lumbar muscles during the fatigue contraction.

6.12 CLINICAL IMPLICATIONS

A distinction might be made between muscle “fatigue” and “ability to fatigue” muscles. It might be speculated that, according to our results, the ability of a person to obtain EMG fatigue during a test with a high force level, would be a sign of good muscular condition and/or better self-efficacy. There would then be a muscular strength margin, when low force contractions are used, like standing, walking or bending. This is also in accordance with physiological training principles. Thus, our results might indicate that exercises would be beneficial for the low-back pain patient. The type of exercise should preferably be resistance exercises in order to activate the type II fibers.

The present EMG test of lumbar muscle fatigue could discriminate patients with long-term low-back pain with a sensitivity of 86%.

A higher initial median frequency by 10 Hz (at L5) and a lower back muscle strength by 1.0 Nm/kg for patients compared to healthy subjects could be considered a clinically relevant difference.

7 CONCLUSIONS

- A combination of several electromyographic frequency variables and MVC with subjective estimates of health-related factors appears to be useful in assessing patients with long-term low-back pain.

- The method has a certain capacity for diagnosis since, using logistic regression, and entering EMG initial median frequency, slope and recovery half-time in combination with MVC, 86% of the patients and 78% of the healthy subjects were correctly classified.

- Patients with not significantly negative slopes, i.e. absent EMG fatigue, had lower self-efficacy and more activity limitations, particularly in activities requiring back muscle endurance, e.g. lifting, carrying and bending down. Thus, the ability to activate the lumbar muscles sufficiently to produce EMG fatigue during an isometric contraction requiring relatively high force seems to be a healthy sign.

- The female patients were characterized by a significantly flatter slope compared to the male patients as well as compared to the healthy men and women. The female patients also had lower scores than the male patients in physical functioning and self-efficacy. This might indicate a higher degree of impaired lumbar muscle function for women.

- The capacity to execute a back extension MVC torque was limited in patients compared to healthy subjects. This might be a reason for the higher initial median frequency at L5 and the flatter slopes at both lumbar levels shown for patients. A higher initial median frequency by 10 Hz (at L5) and a lower back muscle strength by 1.0 Nm/kg for patients compared to healthy subjects could be considered a clinically relevant difference.

- The recovery of the median frequency was exponential-like on group level, and the patients had longer recovery half-time than the healthy subjects. On an individual level, patients with not exponential-like recovery had more activity limitations than patients with an exponential-like recovery indicating possible impairment in lumbar muscle function.

- During an isometric back muscle contraction in seated position, despite a high exertion level in general, EMG fatigue was absent on random electrode sites, in healthy subjects as well as in patients. This might indicate a specific neural driven coordination strategy.

- The initial median frequency and MVC had high reliability, but the slope and the recovery half-time by themselves had not sufficient reliability for clinical follow-ups on an individual level.

8 ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to all those who have supported me during my years of doctorial studies and especially to

Gunnar Németh, Associate Professor, MD, PhD, Head of Department of Orthopeadics, Karolinska Hospital, my main supervisor. Gunnar, enormously encouraging, always friendly and easy-going, always giving support when needed and sharing large scientific and clinical knowledge in interesting discussions focusing on main points. I also thank Gunnar for providing me with computer and other research resources.

Eva Mattsson, Associate Professor, PT, PhD, my co-supervisor and colleague, who always found the time to discuss research questions. Eva, with her large scientific knowledge, has given me very reliable and accurate opinions.

Inga Arvidsson, PT, PhD, my co-supervisor and colleague, who took part in the experiments from the beginning and continuously has assisted me with good advice through the years.

Elisabeth Olsson, Professor, PT, PhD, Deputy Chair, Neurotec Department, for continuous support and for providing me with very good conditions to conduct my doctorial studies at the Division of Physiotherapy.

Andris Kreicbergs, Professor, MD, PhD, Head of the Section of Orthopedics, Karolinska Institutet, for making research facilities available to me.

Karin Harms-Ringdahl, Professor, PT, PhD, Neurotec Department, for always being supportive and friendly, and for sharing her large knowledge in physiotherapy research in interesting and inspiring discussions during seminaries.

David Liljequist, Professor, PhD, co-author, Department of Physics, Stockholm University, for endless high quality support in my research, for reading and contributing to manuscripts and for having inspiring and invaluable discussions on statistical problems and research questions. But most of all for being my life-companion giving love and great support in life situations.

Åsa Dedering, PT, PhD, co-author, college and friend, for many inspiring discussions about the research, good and fruitful collaboration, great helpfulness and sharing things about life.

Elisabeth Berg, Karolinska Institutet, for helpful and valuable statistical advice.

all the physiotherapists who kindly referred patients to me. Especially I want to thank Yousefy Mahr, PT, for his interest and support.

all you people, with and without healthy backs, who participated in the test. Without your generous participation there would not have been any thesis!

all my colleagues at the Neurotec Department, Section of Pysiotherapy, always supporting friends, in good times and in hard times.

my PT collegues Catharina Bexander, Thesese Ljungquist, Marcus Thuresson, Björn Äng for reading the manuscript of this thesis and for constructive comments.

Lennart, my dear old father, for showing such a great interest in my doctorial studies, and for always being there with support, when needed, during all my life.

Ida, my daugther, for just being what you are, the joy of my life.

The work of this thesis was financially supported by grants from the Board of Health and Caring Sciences, Karolinska Institutet, AMF Research Foundation, and Stiftelsen Ann-Mari och Ragnar Hemborgs minnesfond.

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Trötthet och återhämtning i ländryggen – Utvärdering av muskelfunktion hos patienter med långvarig ländryggssmärta och ryggfriska personer

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Stockholm 2002 ISBN 91-7349-391-0

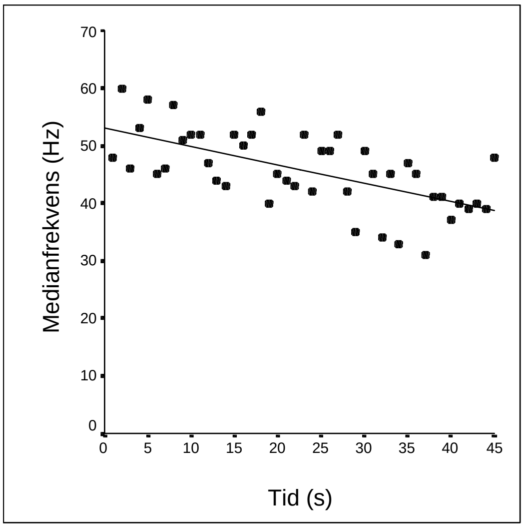
Personer med långvariga, återkommande smärtor i ländryggen (svanken) kan ofta uppleva trötthet i ryggen. Studier har visat att dessa personer ofta har lägre styrka och sämre uthållighet i sina ryggmuskler än personer utan smärttillstånd i ryggen, så kallade ryggfriska personer. Huvudsyftet med denna avhandling var att utvärdera en mätmetod, vilken på ett objektivt sätt antas mäta muskeltrötthet. Mätmetoden heter elektromyografi (EMG).

Under muskelaktivitet, d.v.s. när en muskel spänns (kontraheras), kan man registrera elektriska signaler från muskeln. Dessa kan mätas genom att små elektroder fästs på huden ovanför den muskel som ska undersökas. Våra studier inriktades på ländryggsmuskulaturen och elektroderna applicerades på ryggen bredvid den första och den femte ländkotan, på höger och vänster sida. Sammanlagt testades 57 patienter med långvariga ländryggssmärtor och 73 ryggfriska personer. En del av de ryggfriska personerna deltog endast i våra studier av mätmetodens tillförlitlighet, medan 55 var jämförelsegrupp till ryggpatienterna.

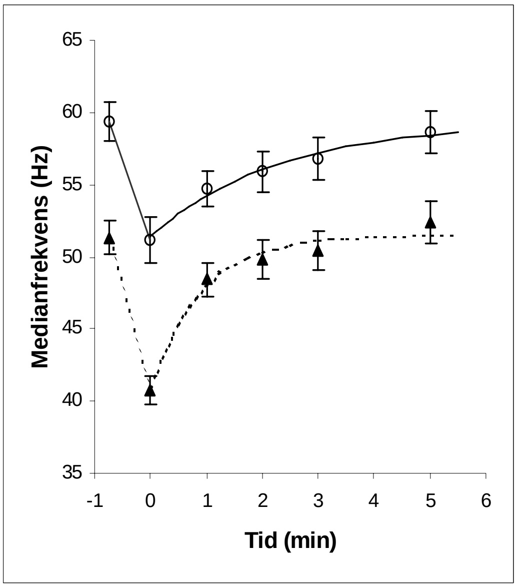
Eftersom vi var intresserade av att undersöka muskeltrötthet, fick försökspersonerna göra ett riktigt rejält uttröttande statiskt muskelarbete. Detta skedde i en styrketräningsmaskin där försökspersonerna väl fixerades med ett bälte över höfterna och ett stöd över knäna. Sedan fick de pressa ryggen bakåt mot en rulle, i skulderbladshöjd, som inte rörde sig. På detta sätt kom de att spänna ryggmusklerna utan någon rörelse. Pressen bakåt skedde med maximal styrka i 5 s, vardera i tre försök. På detta sätt kunde försökspersonernas maximala ryggmuskelstyrka mätas. I momentet därefter gjorde de en uttröttningskontraktion, d.v.s. pressade bakåt under 45 s med en kraft på 80% av den maximala. Under den efterföljande vilan på 5 min, satt de kvar i maskinen och fick göra en 5 s kort kontraktion varje minut. Denna korta muskelkontraktion gjordes för att vi ville undersöka återhämtningsförloppet och EMG kan bara registreras när en muskel är aktiv.

Den elektriska signalen, som registrerades från musklerna, kördes via förstärkare och elektroniska filter in i datorn där den analyserades med hjälp av ett datorprogam så att ett frekvensspektrum kunde erhållas för varje sekund som kontraktionen pågick. Vi valde sedan att använda medianfrekvensen (ungefär mitt-frekvensen) i varje spektrum. I ett diagram över erhållna data kan man se att medianfrekvensen sjunker under en muskelkontraktion som ett tecken på muskeltrötthet. Detta illustreras i figur 1 där varje punkt är medianfrekvensen under en viss sekund. En rät linje har anpassats till punkterna. Linjen har en viss *lutning*, och den kan vara brant eller flack. Värdet där linjen korsar den lodräta axeln har kallats den *initiala medianfrekvensen*. I figur 2 visas uttröttnings- och återhämtningsfasen. Återhämtningen har analyserats genom att anpassa en krökt (exponentiell) kurva till punkterna. Man får då en så kallad halveringstid, vilket är ett mått på hur snabbt återhämtningen går.

För att får reda på om man med mätmetoden skulle kunna särskilja patienter och ryggfriska, användes en statistisk metod som heter logistisk regression. Våra variabler var ryggmuskelstyrka, initial medianfrekvens, lutning och halveringstid. Resultatet av denna analys blev att ca 80% av patienterna och de ryggfriska klassades korrekt, dvs patienterna klassades som patienter och de ryggfriska som ryggfriska. Detta är ett relativt bra resultat.



Figur 1. Medianfrekvensen (registrerat i en av fyra elektroder) under en 45 s lång kontraktion av ryggmusklerna för en individ.



Figur 2. Den genomsnittliga medianfrekvensen under uttröttning (tiden –0.75-0 min) och återhämtning (tiden 0-5 min) för 57 patienter (ringar) och 55 friska personer (trianglar).

Andra statistiska analyser vi gjorde visade att ryggmuskelstyrkan var signifikant lägre hos patienterna än hos de ryggfriska. Vid den femte ländkotan hade patienterna signifikant högre initial medianfrekvens (se figur 2). Lutningen var signifikant flackare för patienterna än för de ryggfriska, speciellt för de kvinnliga patienterna. Återhämtningsförloppet var långsammare för patienterna, vilket syns på den något flackare kurvan i figur 2.

Vad har då dessa skillnader i EMG för betydelse? För att få reda på detta ville vi se om det fanns några samband mellan å ena sidan EMG och å andra sidan olika fysiska aktiviteter och skattningar av hälsa. Patienterna hade därför fyllt i fem frågeformulär, där de bland annat skattade hur mycket deras ländryggssmärtor påverkade hälsan, förmågan att utföra dagliga aktiviteter (t. ex. sitta, stå, gå, lyfta, bära, böja sig, klä på sig) och även självtilliten att klara dessa och liknande fysiska aktiviteter.

Det visade sig, att de patienter (33 st) vars mätvärden visade på mycket flack lutning, nära horisontell, hade signifikant fler begränsningar i aktiviteter och i självtilliten att klara dessa. Begränsningarna gällde t ex personlig omvårdnad (hygien, påklädning etc.), förmåga att lyfta tunga saker, böja sig ner eller gå ner på knä. Den sämre självtilliten gällde t ex hur lång tid man tror sig klara av att bära matkassar. Liknande begränsningar hade de patienter som inte fått något tydligt (exponentiellt) återhämtningsförlopp (25 st) och de vars värden visade på *både* flack lutning och otydlig återhämtning (19 st).

Dessa resultat tyder på att en brant lutning av medianfrekvensen under kontraktionen och en tydlig (någorlunda exponentiell) återhämtning är ett gott tecken. Ryggfriska personer uppvisade ju i högre grad detta mönster och även de ryggpatienter som hade minst aktivitetsbegränsningar. Skulle eventuellt en flack lutning och en otydlig återhämtning kunna vara förenat med någon avvikelse i muskelfunktionen? Ett sådant förhållande skulle kunna bero, antingen på att vissa muskelfibrer har förminskats i storlek på grund av ryggsmärta och sekundärt ändrat rörelsemönster, eller på att dessa patienter helt enkelt inte vågade "ta i" i testet på grund av rädsla för att smärtan skulle förvärras.

Således kan det tänkas att det är ett gott tecken att kunna aktivera sin ryggmuskulatur tillräckligt för att åstadkomma en uttröttning under ett sådant här test. Vidare forskning kan visa hur muskelfunktionen förändras med t ex styrketräning av ryggmuskulaturen hos patienter med långvariga ländryggssmärtor.