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EMG recovery and ratings after back extensor fatigue in patients with lumbar disc herniation and healthy subjects

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Abstract This prospective study aimed to examine whether patients with lumbar disc herniation, before and after surgery, showed impaired recovery from fatigue measured with EMG and subjective ratings as compared to healthy subjects. Forty-three patients due for, and after, lumbar disc surgery and 60 healthy subjects were fatigued using a modified Sørensen's test. Recovery of back extensor muscles was assessed using electromyography and the Borg scale ratings at 1, 2, 3, and 5 minutes of recovery, and was further analyzed using an exponential time-dependence model. The patients completed four questionnaires: the Oswestry, the Roland-Morris, a self-efficacy scale and the SF-36. The exponential time-dependence model was successful for 14 of the 43 patients and 57 of the 60 healthy subjects. The patients for whom the model succeeded had significantly better scores on the questionnaires than those for whom the model was unsuccessful. Specific items related to standing and lifting were identified. The patients' recovery was impaired compared to the healthy subjects, as determined by use of the exponential time-dependence model. The combination of fatigue and recovery measures was reflected in the questionnaire scores and is therefore important for evaluating patients with lumbar disc herniation.

Keywords Electromyography · Lumbar disc herniation · Non-linear regression · Subjective ratings · Recovery

Introduction

People with low-back pain not only fatigue more easily in the back muscles than those without pain but they also have an altered recovery after 1 min (Roy et al. 1990; Peach and McGill 1998). The median frequency slope, a linear regression of the decline in median frequency of an electromyographic (EMG) power spectrum during an isometric muscle contraction, is the most used spectrum parameter indicating muscle fatigue (De Luca 1993). Muscle fatigue results in shorter isometric holding time (endurance) of the back muscles, which is a risk factor for low-back pain (Biering-Sørensen 1984; Luoto et al. 1995; Adams et al. 1999). In patients with low-back pain, people who score themselves as physically active have longer endurance times in the back muscles (Moffroid et al. 1994). Prolonged periods of low physical and sports activity influence the development of back pain (Elfering et al. 2002) and muscle atrophy (Hides et al. 1994). An atrophied back muscle is fatigable (Dolan and Adams 1998). The altered muscle activation pattern due to back pain, i.e. both the excessive fatigue and the impaired recovery, might leave the spinal complex susceptible to further injury.

The definition of recovery may vary among researchers because it depends on pre-set criteria. For example, statistical tests, such as the *t* test (Kroon and Naeije 1988; Häkkinen 1993; Alfonsi et al. 1999), Wilcoxon's test (Hara et al. 1998) or ANOVA (Rodríguez et al. 1993; Tho et al. 1997) have been used to test for the difference between recovery measures and the initial level of the physiological marker used for assessment. The protocol intervals, where measurement intervals range from minutes (Rodríguez et al. 1993) to days (Kroon and Naeije 1991) or weeks (Sbriccoli et al. 2001), set the time to recovery.

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The recovery process can also be described graphically. When a subject rests after a fatiguing contraction, the median frequency measured from back and extremity muscles recovers to the initial level following an exponential curve function of time (Broman et al. 1985; Kuorinka 1988; Vestergaard-Poulsen et al. 1995; Alfonsi et al. 1999; Elfving et al. 2002). An exponential (non-linear) model is superior to models anticipating linearity in the analysis of metabolic changes during muscle contraction and recovery (Simond et al. 2001). For a recovery process following an exponential curve function, a recovery half-time (Elfving et al. 2002) may be preferable. This is analogous to measures of other phenomena in nature.

Subjective factors such as self-efficacy beliefs and fear-avoidance influence physical performance (Estlander et al. 1994; Pincus et al. 2002). For a complete assessment of fatigue, objective measures such as EMG and endurance times as well as the subjects' own ratings are needed (Dedering et al. 2002). Subjective ratings of fatigue correspond well to the median frequency slope (Dedering et al. 1999) and also reflect the difference between patients and normal subjects regarding the fatigue experience (Taimela et al. 1998). Subjective ratings during recovery have also been measured (Tho et al. 1997; Elfving et al. 2002) but need further investigation.

Patients with lumbar disc herniation differ from other patients with low-back pain in that most suffer from sciatica, though some also have pain from the lower back (Vroomen et al. 1999). Studies of lumbar disc herniation found patients to be more fatigued and have shorter endurance times than healthy subjects (Dolan et al. 2000; Dedering et al., in preparation). By analogy with low-back pain, one would assume that patients with lumbar disc herniation have a poorer recovery process than healthy subjects.

In a former study by our group (Dedering et al., in preparation), we investigated back-muscle fatigue and endurance in patients with lumbar disc herniation. In the present study we wanted to investigate whether patients, before and after surgery, had an impaired recovery process after fatigue according to the use of an exponential time-dependence model, when compared to healthy subjects. Additionally, we investigated the

between-days reliability of recovery measurements in healthy subjects.

Methods

Subjects

Forty-three patients (Dedering et al. in preparation) with lumbar disc herniation and no previous history of spinal surgery participated in the study, both before and 4 weeks after undergoing lumbar microdiscectomy. Patients' herniations were at the L4–5 or L5–S1 level and fulfilled the pre-set criteria for surgery. Fifty subjects (Dedering et al. 1999) without back pain during the previous year (medical students) served as a control group. Ten other subjects (Dedering et al. 2000) without back pain (physical therapy students and colleagues) participated in the reliability study. Subjects' characteristics (mean and SD for age, weight, height and BMI) are presented in Table 1. Age differed significantly ($P < 0.001$) between the healthy subjects and the patients. However, a recent review reports that age does not influence endurance time for extremity muscles (Allman and Rice 2002). This difference is therefore not thought to affect the results. The Ethics Committee at the Karolinska Hospital approved the study and all subjects gave their informed consent to participate.

Test procedure

All participants performed a modified Sørensen's test (Dedering et al. 1999). The Sørensen's test is a prone lying endurance test to exhaustion, originally performed with straight hips (Biering-Sørensen 1984). The modification was to have the hips flexed 40°, which reduces the influence from the hip extensors (Németh and Ohlsén 1985). When the test was ended, 5 s contractions were performed after 1, 2, 3 and 5 min of rest to test recovery from fatigue. Results from the fatiguing contraction of the three different groups of subjects have been presented in two previously published articles (Dedering et al. 1999, 2000).

Table 1 Characteristics for all participants. Mean (SD) for age, weight, height and BMI ($n = 103$)

Participants	Age, years		Weight, kg		Height, m		BMI, kg·m ⁻²	
	Men	Women	Men	Women	Men	Women	Men	Women
Patients ^a	42.2 (11.5)	42.2 (10.4)	82.7 (9.5)	69.7 (12.3)	1.80 (0.06)	1.68 (0.06)	25.5 (3.4)	24.7 (3.4)
Subjects ^b	26.5 (3.9)	27.6 (5.4)	78.7 (8.7)	59.2 (7.4)	1.82 (0.07)	1.67 (0.07)	23.8 (2.2)	21.3 (2.7)
Subjects ^c	42.5 (10.6)	31.5 (11.1)	86.0 (12.7)	60.1 (5.8)	1.80 (0.07)	1.67 (0.05)	26.7 (3.7)	21.4 (1.4)

^a $n = 43$, (men = 27, women = 16) (Dedering et al., in preparation)

^b $n = 50$, (men = 25, women = 25) (Dedering et al. 1999)

^c $n = 10$, (men = 2, women = 8) (Dedering et al. 2000)

EMG

After cleaning the skin of the lower back with alcohol, four pairs of surface electrodes (Blue Sensor N-00-S, Medicotest A/S, Denmark) were attached over the erector spinae muscles on the left and right sides of the L1 and L5 spinous processes. The intra-electrode distance at each electrode site was 20 mm. A ground electrode was placed at the left lateral malleolus (Blue Sensor VL-00-S, Medicotest). EMG signals from four channels were transmitted telemetrically (Telemyo 16, Noraxon, USA), A/D converted and stored in a personal computer. The sampling frequency was 1,000 Hz and the bandwidth 10–800 Hz. A high-pass filter of –12 dB/oct and a low-pass filter of –30 dB/oct were used. Fast Fourier transform was calculated for every second using the Noraxon software. The aliasing effect due to excessive bandwidth was tested for and did not affect the results.

Borg CR-10 scale

All participants rated their perceived fatigue, and the patients also their back and leg pain, on a Borg CR-10 scale (Noble et al. 1983). Ratings were obtained before and during the modified Sørensen's test and straight after the test contractions at 1, 2, 3 and 5 min of recovery. The Borg CR-10 scale ranges from 0 to 10 and the numbers are supported by written expressions. Subjects received both verbal and written instructions of how to use the scale. They were told to first look at the written expressions and then choose the number corresponding to the most appropriate statement, which was noted by the examiner.

Test-retest reliability

The ten back-pain-free participants in the reliability test were tested on three different occasions following the protocol described above. All tests were done in the afternoons, on three separate days, separated by 5–7 days. To ensure the same electrode placement every session, a transparent template was made at the first session.

Additional assessments of the patients with lumbar disc herniation

At the test sessions, before and 4 weeks after surgery, the patients were clinically examined, rated their back and leg pain and filled out four different questionnaires: (1) the Oswestry disability questionnaire (Fairbank et al. 1980), (2) the Roland-Morris disability questionnaire (Roland and Morris 1983; Johansson and Lindberg 1998), (3) the self-efficacy scale (Estlander et al. 1994) and (4) the generic Medical Outcomes Study Short Form 36 item questionnaire (SF-36) (Sullivan et al. 1995).

Dropouts

Thirty-four of the 43 patients completed both tests including the recovery measures. The reasons for not attending were hospital treatment (two) or pain (seven). When comparing the nine dropouts with the 34 patients with two complete tests, no significant difference was present for the straight-leg raising test and the Roland-Morris questionnaire at inclusion. Seven of the nine dropouts performed the endurance test before surgery and had significantly ($P=0.04$) shorter endurance times than those with two complete tests. For the healthy subjects, all completed the test but the EMG recordings from one woman were affected by technical disturbances and therefore excluded.

Data analysis

Median frequency during recovery

From the fatiguing contraction, initial median frequency (f_i) and end median frequency (f_e) were calculated as the mean of the first and the last 5 s, respectively. During recovery, the mean of the median frequencies for the respective 5 s contractions at 1 min (f_1), 2 min (f_2), 3 min (f_3) and 5 min (f_5) after the end of the fatiguing contraction, was calculated. A graphical visualization of the data set (f_e, f_1, f_2, f_3, f_5) implied that the recovery process followed an exponential curve function.

The exponential, time-dependence model of recovery

The exponential, time-dependence model of recovery for the median frequency was introduced in an earlier study by our group (Elfving et al. 2002). Briefly, a model for the recovery process of the median frequency F was assumed to be:

$$F(t) = (F_i - F_e) \cdot (1 - e^{-t/\tau_F}) + F_e \quad (1)$$

where F_i was the initial median frequency estimate, F_e the end median frequency estimate and τ_F the recovery time constant estimate.

The above parameters were derived from a curve-fitting process to measured data using a non-linear regression analysis in SPSS (version 11.0). Figure 1 illustrates the fitted curve parameters and measured data during the phases of fatigue and recovery. Note that F (upper case) denotes an estimate from the curve fitting process while f (lower case) refers to measured data. The end median frequency (f_e) was considered the start of the recovery process, i.e. $t=0$ min. The initial median frequency (f_i) was assigned to represent the asymptotic value at infinite time after recovery. The f_i value could be used because no overshooting was observed in the data. A time of 100 min was set for the f_i value to represent infinity numerically. Input data for each subject were then f_e ($t=0$ min), f_1 ($t=1$ min), f_2 ($t=2$ min),

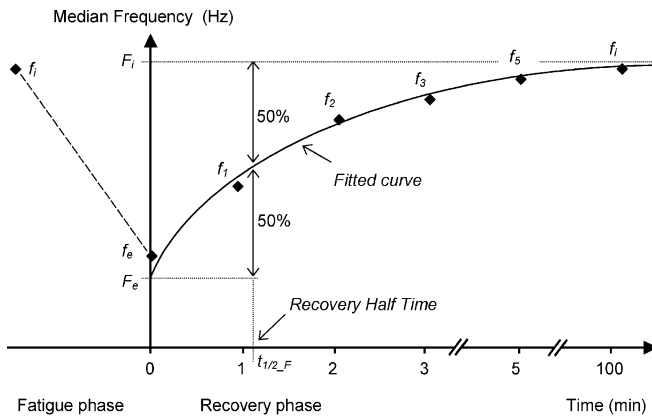


Fig. 1 Illustration of fitted curve parameters (F_i , F_e), recovery half-time $t_{1/2_B} = \tau_B \cdot \ln(2)$ and measured data (f_i , f_e , f_1 , f_2 , f_3 , f_5) during phases of fatigue and recovery. F_i and F_e are estimates of the fitted curve

f_3 ($t=3$ min), f_5 ($t=5$ min), and f_i ($t=100$ min), for each electrode site respectively. An estimation of $F_i - F_e$, F_e and τ_F was determined by the fit. A coefficient of determination (R^2) indicated how well data were fitted. Half-time median frequency recovery ($t_{1/2_F}$), i.e. the time when the median frequency had recovered 50% of its decrement, was then defined as:

$$t_{1/2_F} = \tau_F \cdot \ln(2) \quad (2)$$

where $\ln(2)$ was the natural logarithm of 2 (equals 0.693).

Borg ratings during recovery

Borg ratings before the test started (b_i), at the end of the fatiguing contraction (b_e), and during recovery at 1 min (b_1), 2 min (b_2), 3 min (b_3), and 5 min (b_5) were used in the analysis. A graphical visualization of the data set (b_e , b_1 , b_2 , b_3 , b_5) implied that the recovery process followed an exponential curve function. The trend of the ratings was inverse to the median frequency, i.e. ratings increased with fatigue and decreased during recovery. For the Borg ratings, a similar approach was used as for the median frequency, although Borg ratings are often considered categorical data. A model for the recovery process of the Borg ratings B was assumed to be:

$$B(t) = (B_e - B_i) \cdot e^{-t/\tau_B} + B_i \quad (3)$$

where B_e was the end Borg rating estimate, B_i the initial Borg rating estimate and τ_B the recovery time constant estimate.

Analogously to the median frequency, the above parameters were derived from a curve-fitting process to measured data using a non-linear regression analysis. B (upper case) denotes the estimate from the curve-fitting process while b (lower case) refers to measured data. Input data in the non-linear regression analysis for each subject were b_e ($t=0$ min), b_1 ($t=1$ min), b_2 ($t=2$ min),

b_3 ($t=3$ min), b_5 ($t=5$ min), and b_i ($t=100$ min). An estimation of $B_e - B_i$, B_i and τ_B was determined by the fit. Recovery half-time on the Borg ratings ($t_{1/2_B}$) was then defined as:

$$t_{1/2_B} = \tau_B \cdot \ln(2) \quad (4)$$

Classification

To determine the success of the recovery model, subjects were classified into four defined categories. Since recovery is regarded as the opposite of fatigue, a prerequisite for examining recovery was that fatigue was reached after the exhausting contraction. Reasons for not accepting the subject's results of the model were that either one or both of the following occurred in one or more electrode sites: there was no sign of fatigue from the exhausting contraction, i.e. the slope was not significantly different from zero, and/or the τ_F -values were either extremely small (<0.1 min) or extremely large ($>10,000$ min) meaning that to describe recovery using the exponential model was not applicable.

The resulting four possible combinations (categories A, B, C and D) for determining recovery from fatigue and the applicability of exponential time-dependence model are shown in Table 2. For category A the recovery model was regarded as successful and for categories B, C and D not successful. In some cases a relatively high R^2 was found even though the τ_F -values were considered extreme. These cases were also considered as a failure of the exponential model.

For the Borg ratings, two categories were identified. The time dependence model could either be regarded as applicable or not. If the τ_B -values were either extremely small (<0.1 min) or extremely large ($>10,000$ min) the exponential model was regarded as inapplicable.

The classifications of recovery using median frequency and Borg ratings respectively were used in between-group comparison of the endurance time of the fatiguing contraction (time to exhaustion rounded down to the closest 5 s), and the questionnaire answers.

Statistics

Data plots of the half-time median frequency recovery ($t_{1/2_F}$), showed data distribution to be positively skewed. After a log transformation, the data conformed well to the normal distribution and were therefore

Table 2 The four possible combinations (categories A, B, C, D) for determining the classification based on whether fatigue was present, i.e. whether the regression line from the fatiguing contraction diverged significantly from zero (fatigued), and the appropriateness of describing recovery using the exponential time-dependence model

	Exponential	Non-exponential
Fatigued	A	B
Not fatigued	C	D

considered to be log-normally distributed. Parametric statistics were applied and the data were then inversely transformed. To describe the data, mean and 95% confidence intervals (95% CI) were calculated. For the patients, repeated-measures ANOVA with the within-subject factors surgery, level and side was used. In the repeated-measures ANOVA used for the healthy subjects, level and side were within-subject factors and gender was added as between-subject factor. The patients before and after surgery were also compared with the healthy subjects using an independent samples *t* test. For all the questionnaire items, a Kruskal-Wallis ANOVA was used to decide whether the four categories identified from the median frequency recovery differed significantly. For post hoc analysis, a Mann-Whitney U test was used. This test was also used to decide whether the two categories identified from the Borg rating recovery differed significantly regarding the questionnaire items. Reliability for the half-time median frequency recovery ($t_{1/2_F}$) was described using intra-class correlation coefficients (ICC) (Fleiss 1986). The reliability of the Borg scale ratings at 1, 2, 3 and 5 min of recovery was evaluated using a model where the percentage of agreement between test sessions was calculated (Svensson 1998).

Results

Thirty-four patients (25 men and 9 women) completed the test both before and 4 weeks after surgery. Table 3 shows the number of subjects in each of the four categories defined for the median frequency fatigue and recovery. These four categories served as a base for further analysis. The model was successful for all electrode sites at both tests on 14 patients (12 men and 2 women). Only these patients were included in further analysis of the half-time median frequency recovery ($t_{1/2_F}$). For 46 of the 49 healthy subjects the model was successful. For the ten subjects in the reliability study the model was also successful.

Table 3 Number of patients and subjects where one or more electrode sites were affected. The regression line from the fatiguing contraction diverged significantly from zero (fatigued) or did not (not fatigued). The exponential time-dependence model was appropriate for describing recovery (exponential) or not (non-exponential)

	Exponential		Non-exponential	
	Before surgery	After surgery	Before surgery	After surgery
Patients				
(n = 34)				
Fatigued	24	19	3	9
Not fatigued	4	1	3	5
Healthy subjects				
(n = 49)				
Fatigued	46		3	
Not fatigued	0		0	

Table 4 Half-time (s) median frequency recovery for patients ($n = 14$) before and after surgery, and for healthy subjects ($n = 46$), mean (95% CI)

Muscle	L1 right	L1 left	L5 right	L5 left
Before	77 (52–112)	76 (48–121)	115 (73–182)	77 (48–124)
After	67 (44–103)	107 (66–175)	141 (93–212)	138 (97–197)
Healthy	77 (64–92)	101 (77–132)	99 (81–120)	96 (78–117)

Half-time median frequency recovery

Patients

The $t_{1/2_F}$ for the patients did not change significantly before compared to after surgery ($P = 0.093$) (Table 4). The patients had significantly longer $t_{1/2_F}$ at the L5 level than at the L1 level ($P = 0.042$). For the patients, the median of the coefficient of determination of the fit (R^2) for all electrode sites before surgery was 0.90 (range 0.43–0.99) and after surgery 0.92 (range 0.05–0.99).

Healthy subjects

In the healthy subjects, women had significantly longer $t_{1/2_F}$ than men for all recording sites ($P = 0.051$) (Table 5). No significant difference between the lumbar levels was found ($P = 0.105$). For the healthy subjects the median R^2 was 0.95 (range 0.30–0.99).

Correlation between $t_{1/2_F}$ and endurance time and median frequency slope

Patients

Before surgery, the Pearson correlation coefficients between $t_{1/2_F}$ versus endurance time and median frequency slope ranged from 0.03 to 0.36 (absolute values). After surgery the correlation coefficients ranged from 0.07 to 0.52 (absolute values).

Healthy subjects

For healthy subjects the corresponding correlation coefficients between $t_{1/2_F}$ versus endurance time and median frequency slope ranged from 0.01 to 0.20 (absolute values).

Table 5 Half-time median frequency recovery (s) for the healthy subjects (men = 23, women = 23), mean (95% CI). A significant difference between men and women was found ($P = 0.051$)

Muscle site	L1 right	L1 left	L5 right	L5 left
Men	74 (57–97)	79 (62–100)	87 (65–117)	79 (59–107)
Women	79 (60–104)	128 (95–173)	113 (86–147)	115 (89–150)

Recovery of the Borg ratings

The Borg ratings recovered inversely to the median frequency (Fig. 2).

Patients

For 20 patients (14 men and 6 women), the exponential time-dependence model was successful both before and after surgery (exponential recovery). These were the 14 for whom the model for recovery of the median frequency worked, and six additional patients. For the remaining 14 patients, the model was unsuccessful (non-exponential recovery). The patients for whom the model succeeded ($n=20$) had a median R^2 before surgery of 0.96 (range 0.80–0.99) and after surgery 0.97 (range 0.63–0.99). The mean (95%CI) recovery half-time on the Borg ratings ($t_{1/2_B}$) before surgery was 54 s (31–94) and after surgery 47 s (28–78). No significant difference was present for the results before surgery compared to after surgery, or to the healthy subjects.

Healthy subjects

Among the healthy subjects, the model did not work for one woman (for her, the median frequency model was also unsuccessful). For the healthy subjects where the model succeeded ($n=49$), the median R^2 was 0.98 (ranging from 0.90 to 0.99). The mean (95%CI) $t_{1/2_B}$ for all was 43 s (36–50), for men 47 s (37–58) and for women 39 s (30–50). No significant gender difference was present.

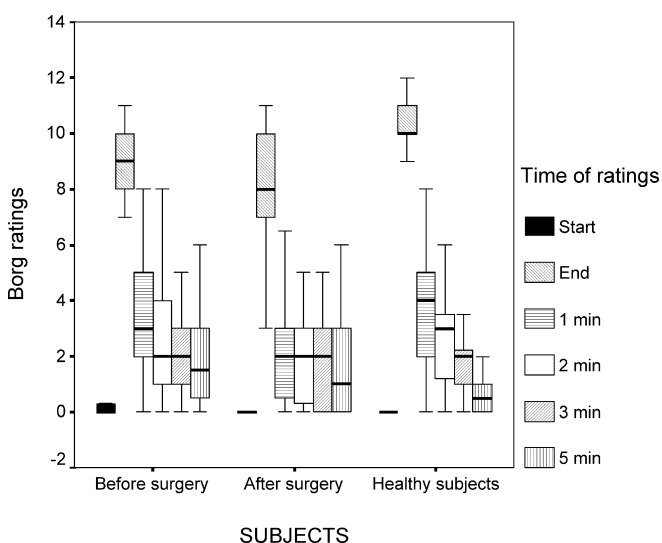


Fig. 2 Box plot of Borg ratings of perceived fatigue during the recovery process for patients before and after surgery, and for healthy subjects. The *boxes* represent the interquartile range which contains 50% of the values. The *whiskers* show the extremes. The *lines* across the *boxes* indicate the median

Recovery classification in relation to endurance time

Patients

For the patients there was no significant difference in endurance time for the contraction to exhaustion before or after surgery between the four categories that had been formed from median frequency recovery established before surgery (range 65–405 s). The patients for whom the Borg ratings had a non-exponential recovery process had significantly shorter endurance times both before and after surgery than those with an exponential recovery process.

Healthy subjects

For the three healthy subjects where the model was considered not to apply (category B, 2 men, 1 woman), the endurance times were 315, 520 and 535 s respectively (the whole-group ($n=50$) mean was 383 s).

Patients' recovery classification in relation to activity limitations, self-efficacy and health

For patients in category D (not fatigued, non-exponential recovery) significantly more ability limitations, lower self-efficacy and health status were rated compared to patients in the other categories. For the Roland-Morris questionnaire, there was a significant difference both before and after surgery between the four established categories of median frequency recovery ($P=0.016$). Category D had significantly higher scores, reflecting more ability limitations, than categories A (fatigued, exponential recovery) and B (fatigued, non-exponential recovery). Post hoc Bonferroni P values were 0.023 and 0.027, respectively. No significant difference for the Roland-Morris was found between the categories classified by Borg rating recovery.

From the Oswestry disability questionnaire, the items "pain" and "standing" differed significantly between the four categories of median frequency recovery. For the self-efficacy questionnaire, the items "standing" and "biking" differed significantly and for the SF-36, the item "physical functioning" differed significantly (see Table 6). For the two recovery categories identified for recovery of the Borg ratings before surgery, significant difference was present for the Oswestry item "lifting" ($P=0.007$) and the self-efficacy item "carrying" ($P=0.024$).

Reliability for healthy subjects

For half-time median frequency recovery ($t_{1/2_F}$), the intra-class correlation coefficients were 0.54, 0.13, 0.44, 0.49 for L1 right and left and L5 right and left, respectively. For the Borg ratings at 1 min recovery, agreement ranged between 20 and 40%. For the Borg ratings

Table 6 Results for the Kruskal-Wallis ANOVA and post-hoc Mann-Whitney U tests (corrected for ties) for questionnaire items before surgery that differed significantly between recovery categories A (fatigued, exponential recovery), B (fatigued, non-exponential recovery), C (not fatigued, exponential recovery) and D (not fatigued, non-exponential recovery) ($n=37$). Only P values <0.05 are presented

	Kruskal-Wallis	Post hoc Mann-Whitney U test between categories:					
		A-B	A-C	A-D	B-C	B-D	C-D
Oswestry							
Pain	0.030	–	–	0.013	–	–	–
Stand	0.038	–	–	0.035	–	0.040	0.017
Self-efficacy							
Standing	0.046	–	–	0.016	–	–	0.028
Biking	0.016	0.025	–	0.018	–	0.022	–
SF-36							
Physical functioning	0.011	0.026	–	0.015	0.048	0.032	0.041

at 2 min recovery, the actual percentage agreements in relation to the maximum possible (PA/PA_{max}) were: 30%/20% for test 1-test 2, 40%/20% for test 1-test 3 and 60%/70% for test 2-test 3. For the Borg ratings at 3 and 5 min, the subjects rated 0–3, indicating they felt recovered. The agreement ranged between 10 to 40%.

Discussion

The patients for whom the exponential time-dependence recovery model was successful were few compared with the healthy subjects. Anticipating the accuracy of the model, i.e. the recovery process should follow an exponential curve function, the recovery process was impaired in patients with lumbar disc herniation. However no significant difference was found between the patients and the healthy subjects in half-time median frequency recovery, perhaps because only the “non-impaired” patients could be included in analysis of half-time median frequency recovery. Significant fatigue was a prerequisite for recovery analysis. When the patients failed to fatigue the analysis of recovery half-time was predicted to fail. The other prerequisite was that the patients should have non-impaired recovery. Consequently, only the “non-impaired” patients were included. We therefore believe that, for our patients, dichotomizing the patients depending on the appropriateness of the exponential model was of greater value than the recovery half-times. That the patients for whom the model succeeded had significantly better questionnaire scores than those for whom it failed strengthens this theory.

Limitations with the current protocol used for measuring recovery concerned the time for recovery measures and the number of measurements used. First, relatively few contractions were used to measure recovery. The curve fit to few measured data points is uncertain, which might explain the large variability in the coefficients of determination of fit (R^2) and in the

recovery half-times. Secondly, the first measure—after 1 minute of recovery—came relatively late in the recovery process. Recovery was then measured only up to 5 minutes. Yet most of the recovery process was probably covered. EMG recovery in extremity muscles after an isometric contraction is most rapid within the first minute (Rodriquez et al. 1993) and complete after 5 minutes (Kuorinka 1988). Thirdly, the 5 s contractions used to measure fatigue might have been fatiguing themselves, thus affecting the measurement of the recovery process. Because of the risk of interfering with the recovery process itself, we tried to keep the number of measures to a minimum. However, muscle fatigue is not generally manifested through EMG signals during such short contractions (Larivière et al. 2001).

The findings of the recovery classification used in the current study are of clinical relevance for patients with lumbar disc herniation. The combination of fatigue and recovery specifically reflects patients’ impairments. From the questionnaires, the items concerning “standing” ability and self-efficacy belief about “standing” were identified by the categories of the median frequency. From the classification of the subjective assessments, the items concerning “lifting” ability and self-efficacy beliefs about “carrying” were identified. Clinically, standing reflects ability which is thought to stress fatigue in the lower back. Patients with low-back pain often complain of fatigue when standing for a long time. Lifting technique is considered important for the back muscles (Hoogendoorn et al. 2000). Numerous studies assess lifting ability and positions, both for identification of back patients and to define the appropriate way of lifting objects (Dolan et al. 1994; Dolan and Adams 1998; Kollmitzer et al. 2002; Larivière et al. 2002a). In work rehabilitation programs, awareness and training of lifting techniques are considered crucial (Lu et al. 2001; Prather et al. 2002) however not evidently beneficial (van Poppel et al. 1998). The current findings, however, indicate that special attention should be given to activities related to standing and lifting in patients with lumbar disc herniation. The relatively few patients in categories B-D might be of concern for generalization and implementation of the findings from the classification. The Kruskal-Wallis test is appropriate for small sample sizes and was adjusted for this. Since a statistically significant difference was found, the average ranks from categories A-D were so disparate that they could be regarded as having been drawn from different populations. However, further studies including more patients with back pain are needed to confirm the current results.

Concomitant with back pain, a change in muscle structure has been reported as atrophied type I- and type II muscle fibers in patients with lumbar disc herniation (Zhu et al. 1989) at the spinal level involved (Yoshihara et al. 2001; Zhao et al. 2000). A significant change after compared to before surgery in median frequency from the fatiguing contraction was found only at the L5 level (Dedering et al. in preparation). The same phenomenon

was seen in the present study where patients had significantly longer half-time median frequency recovery for the L5 than the L1 level. The L5 disc was affected and the pain originated from the lower lumbar levels. No significant difference was found before compared to after surgery. However, the present between-days reliability of the recovery measures was low and accorded with that in other studies where ICC ranged between 0.045 and 0.45 (Peach et al. 1998; Larivière et al. 2002b).

Low correlation was found between endurance time and median frequency slope versus recovery half-times. Low correlation between recovery half-times and the median frequency slope was found by our group when applying the same analysis method to a protocol with short contractions of high effort (Elfving et al. 2002). We therefore believe recovery to be a physiological phenomenon with constancy. Short recovery times have been found for protocols with high force levels (Rodríguez et al. 1993; Linnamo et al. 1998; Elfving et al. 2002). The longer recovery times after contractions of lower force are reportedly due to greater involvement of peripheral factors than in recovery after maximum contraction, where a more central component is suggested (Linnamo et al. 1998). Fatigue is considered task-dependent (Enoka 1995). The recovery process could also be considered task-dependent. Recovery half-time might be constant for each constitutionally different protocol.

An interesting phenomenon observed in the current study was the fewer patients significantly fatigued after the fatiguing isometric contraction compared to the healthy subjects. The current protocol was evidently sufficient to fatigue back muscles in healthy subjects. Our patients had, after improvement with surgery, about one half (men) to one third (women) of the healthy subjects' endurance times (Dedering et al. in preparation). The patients, probably due to pain and reduced physical capacity, ended the contraction too early to fatigue the back muscles. The higher body mass in the female patients compared with the controls might also have contributed to the low endurance times. In an earlier study on healthy subjects, where 80% of a maximal voluntary contraction (MVC) was held for 45 s (Elfving et al. 2002), only 42% were significantly fatigued. The explanation might have been difficulties in performing MVC or varying muscle co-ordination. The present patients might however have an altered activation pattern in the back muscles resulting in inability to fatigue a particular muscle. The back pain associated with lumbar disc herniation could lead to reflex inhibition of a muscle contraction and pain is sometimes manifested as pain-induced lumbar scoliosis (Matsui et al. 1998). Another possibility is that type II muscle fiber atrophy is present as reported previously in patients with disc herniation (Yoshihara et al. 2001; Zhao et al. 2000; Zhu et al. 1989). This would result in a greater proportion of type I fibers which may lead to a slower rate of decline in median frequency (Mannion et al. 1998).

Patients with non-exponential recovery on the Borg rating scales had lower endurance times than those with an exponential recovery. The reason might be that endurance time is influenced by psychological factors which might affect the subject's motivation (Mannion et al. 1996), as are Borg ratings. The fitting of the Borg ratings to the exponential time-dependence model was appropriate according to coefficients of determination (R^2). The R^2 values for the recovery of Borg ratings were higher than the R^2 values for the recovery of median frequency. To treat categorical data as continuous is controversial. By fitting data to a line, an assumption of continuation was made, even though we had no idea of the ratings in between the assessments. The ratings were mostly integers, even though decimal ratings were accepted. The $B_e - B_i$, B_i and τ_B were estimates determined by the fit of the non-linear regression, and could be decimal values, disparate from the original rating. However, it is interesting that the recovery measures obtained with a rating scale follow an exponential function well. According to Borg, the ratings could be treated as continuous data (Borg 1998). The Borg ratings were most reliable between the second and third test, indicating a need for a practice session. The same tendency was shown for the Borg ratings of fatigue presented in an earlier study (Dedering et al. 2000).

The healthy women in the present study had significantly longer half-time median frequency recovery than healthy men. In extremity muscles, women have proved to recover faster than men, regarding both EMG and force (Häkkinen 1993; Linnamo et al. 1998; Fulco et al. 1999). In these studies high force fatiguing contractions were used. It is difficult to compare extremity muscle data with those from back muscles because the latter, with their postural function, are constitutionally different (Mannion 1999). The longer half-time median frequency recovery might be due to muscle fiber composition. Endurance times of the lower back muscles are reportedly longer in women than men and women have a lesser decline in median frequency slope (Mannion and Dolan 1994; Mannion et al. 1998) probably because women have relatively more type I muscle fibers (Thorstensson and Carlsson 1987; Mannion et al. 1997) with greater oxidative capacity. Analogously, slow recovery in elderly is suggested due to more type I fibers, reduced metabolic capacity and membrane potential propagation than younger people (Hara et al. 1998).

In conclusion, the patients had an impaired recovery process as determined by the use of the exponential time-dependence model. The combination of fatigue and recovery measures was reflected by the questionnaire scores and clinically, special attention should be given to activities related to standing and lifting in patients with lumbar disc herniation. We believe that dichotomizing the patients depending on whether or not they had an exponential recovery process mirrors important impairments and therefore was of greater value than the calculated recovery half-times for the present patients.

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