Assessment of the validity of the Biering-Sørensen test for measuring back muscle fatigue based on EMG median frequency characteristics of back and hip muscles

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Abstract

The aims of the present study were (1) to investigate the differences in median frequency characteristics between back and hip muscles of healthy subjects during a Biering-Sørensen test, (2) to determine if the Biering-Sørensen test is a valid test for measuring back muscle fatigue, and (3) to standardise the Biering-Sørensen test by using objective movement analysis when defining endurance time, and compare this to the original method based on tactile feedback. Twenty healthy subjects participated in this experiment. The electromyographic activity of eight back and hip muscles was bilaterally measured. In addition three-dimensional data of the lumbar region were collected with an ultrasound movement analysis system. Median frequencies were computed from the EMG power spectra. Two methods of determining the endurance time of the Biering-Sørensen test yielded highly correlated but significantly different normalized median frequency slope values (NMF slope). Significant differences in NMF slope values between several back and hip muscles could be demonstrated. Low to moderate correlation coefficients were shown between NMF slope values and endurance time. Multiple stepwise linear regression analyses revealed that only NMF slope of the thoracic part of the iliocostalis lumborum muscle could significantly predict the test endurance time. The findings of the present study support the validity of the Biering-Sørensen test for measuring back muscle fatigue.

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1. Introduction

The electromyographic (EMG) spectrum analysis has been widely used to monitor the development of localized muscle fatigue (Biedermann et al., 1990; Dolan et al., 1995; Koumantakis et al., 2001; Mannion et al., 1997, 1998; Mannion and Dolan, 1994; Mayer et al., 1989; Ng and Richardson, 1996; Ng et al., 1997; Tsuboi et al., 1994; Van Dieën et al., 1993). Fatigue causes a decrease of the frequency content of the EMG signal, usually described as a decline of the mean power or median frequency parameters of the EMG power spectrum. The Biering-Sørensen test, a trunk holding test in an antigravity prone position, is commonly used to measure the endurance capacity of the back muscles (Biering-Sørensen, 1984; Chok et al., 1999; Cooper and Stokes, 1994; Mannion and Dolan, 1994; Ng and Richardson, 1996; Ng et al., 1997; Tsuboi et al., 1994; Umezu et al., 1998).
The change in the median frequency of the EMG spectrum obtained during this test has been shown to be a better predictor of first-time low back pain (LBP) acquisition than the simple measure of endurance time (Mannion et al., 1997). On the other hand, Adams et al. reported that the median frequency parameters were not significant predictors of first-time LBP, although endurance time during the Biering-Sørensen was (borderline) significant at some of their follow-ups (Adams et al., 1999). Several studies however have shown that chronic LBP patients often suffer from excessively fatigable back extensor muscles (Biering-Sørensen, 1984; Chok et al., 1999; Jorgensen and Nicolasen, 1987; Mayer et al., 1989; Roy et al., 1989; Tsuboi et al., 1994).

Despite recommendations of several authors (Mannion et al., 1997; Roy et al., 1989; Sparto et al., 1997), most studies analyzing back muscle fatigue have relied on analyses of EMG signals detected from only a few muscle locations (Biedermann et al., 1990; Koumantakis et al., 2001; Mannion and Dolan, 1994; Ng and Richardson, 1994; Ng et al., 1997). The back muscles cannot be accurately assessed as one homogeneous muscle mass because they are composed of several fascicles that act synergistically to produce trunk extension tasks (Larivière et al., 2002). Moreover, Mannion and Dolan (1994) have found that endurance time during an isometric back extension task is highly correlated with the muscle that shows the greatest decline in median frequency than any one muscle alone. Therefore it is important to simultaneously measure several muscle locations in order to avoid a reduced and oversimplified view of the EMG trunk muscle performance (Matthieu and Fortin, 2000; Roy et al., 1989; Tsuboi et al., 1994). Relevant within this context is that Macintosh and Bogduk showed that the erector spinae muscle consists of two muscles – the iliocostalis lumborum and longissimus thoracis – each with distinct thoracic and lumbar parts (Macintosh and Bogduk, 1987). However, to the authors’ current knowledge no previous studies have reported simultaneously collected electromyographic data from these four different parts of the erector spinae muscles during a Biering-Sørensen test. During this test it was also demonstrated that the hip extensor muscles (gluteus maximus and biceps femoris) showed muscle fatigue, which was closely related to the test endurance time (Kankaanpää et al., 1998). Consequently, the validity of the Sørensen back endurance test to measure specifically the paraspinal localized muscle fatigue has been questioned (Kankaanpää et al., 1998).

Furthermore, it has been shown that – among other factors (e.g. changes in muscle force, displacement of electrodes, motor unit synchronization, etc.) – the frequency content of the EMG signal can be altered by variations in muscle length throughout the test (Mannion and Dolan, 1996; Sparto et al., 1999). Because the length of the erector spinae muscles is largely determined by the curvature of the lumbar spine in the sagittal plane (Dolan et al., 1995; Mannion and Dolan, 1996), measurements of the lumbar lordosis of the subject should be taken into account when studying EMG trunk muscle results. Few authors, however, have incorporated recordings of the posture of the subject during the Biering-Sørensen test (Chok et al., 1999; Mannion et al., 1997; Mannion and Dolan, 1994; Ng and Richardson, 1996; Sparto et al., 1997).

The aims of the present study were (1) to investigate the differences in median frequency characteristics between back and hip muscles of healthy subjects during a Biering-Sørensen test, (2) to determine if the Biering-Sørensen test is a valid test for measuring back muscle fatigue, and (3) to standardise the Biering-Sørensen test by using objective movement analysis when defining endurance time, and compare this to the original method based on tactile feedback.

2. Materials and methods

2.1. Subjects

Seven males (mean age of 32.9 ± 14.3 years, mean height of 178.7 ± 7.5 cm and mean weight of 76.7 ± 7.8 kg) and 13 females (mean age of 23.5 ± 1.1 years, mean height of 169.1 ± 7.1 cm and mean weight of 61.5 ± 8.0 kg) voluntarily participated in this study. All participants were free of back complaints, had no known pathology, and were habitually active. The local University Hospital’s ethics committee approved the study protocol. Subjects gave their written informed consent prior to participation.

2.2. Design

The subjects had to perform a modified Biering-Sørensen test until fatigue (modified means that the original Biering-Sørensen test was used with minor variations e.g. fewer than three belts to strap the subject’s body or variations in hand position, etc.). Therefore, the subjects were placed in a prone position on an examination couch in such a way that their superior border of the anterior iliac crest was positioned at the edge of the couch and that their upper body was extending beyond the edge of the examination couch. Two belts were used to strap the lower bodies of the subjects (one at the level of the hips, and one just below the knees). During the test the examiner instructed the subjects to maintain their unsupported body in this position as long as possible. The subjects had to hold their hands touching their forehead, with their elbows out to the side and leveled with the trunk. The subjects were also instructed to hold their head in a neutral position, and to look downward at a visual fixation point. Throughout the test verbal instructions and encouragement were given by the examiner. The subjects also received tactile feedback by means of a rope hung up between two vertical stands and placed over their seventh thoracic vertebra (Fig. 1). The EMG activity of eight back and hip muscles was bilaterally recorded during the test and a three-dimensional movement analysis system was used to measure the lumbar curvature of the subjects.

2.3. Equipment

The EMG signals were recorded with a 16 channel surface EMG system (MyoSystem 1400, Noraxon USA Inc., Scottsdale,
AZ). All raw EMG signals were analogue bandpass-filtered between 10 and 500 Hz, amplified (common mode rejection ratio >100 dB, overall gain 1000, noise <1 μV RMS), analogue-to-digital converted (12-bit) at a sampling rate of 1000 Hz. Sixteen pairs of circular surface electrodes with an electrical surface contact of 1 cm² (Ag–AgCl, Blue Sensor, Medicotest GmbH, Germany) were bilaterally attached to the muscles mentioned below. The electrodes were placed within the borders of the muscles, parallel to the muscle fibers and with an interelectrode distance of 25 mm. Before attaching the electrodes, the skin was carefully prepared (hair removal and cleaning of skin with alcohol on the electrode positions). Following electrode locations were used (Fig. 2): gluteus maximus (GM) (midway between the posterosuperior iliac spine and the ischial tuberosity) (Danneels et al., 2001), biceps femoris (BF) (midway between the ischial tuberosity and the lateral epicondyle of the tibia) (Hermens et al., 1999), multifidus (MULT) (2 cm lateral to the midline of the body, above and below a line connecting both posterior superior iliac spines) (Danneels et al., 2002), latissimus dorsi (LD) (3 cm lateral and inferior to the inferior angle of the scapula) (Danneels et al., 2001), longissimus thoracis pars thoracis (LTT) (at the L1 level, midway between the line through the spinous process and a vertical line through the posterosuperior iliac spine) (Macintosh and Bogduk, 1987), longissimus thoracis pars lumborum (LTL) (2 cm lateral at the intersection of a horizontal line through the spinous process of L5 and a line between the interspinous space of L1–L2 and the posterosuperior iliac spine) (Macintosh and Bogduk, 1987), iliocostalis lumborum pars thoracis (ILT) (at the L1 level, midway between the lateral palpable border of the erector spinae and a vertical line through the posterosuperior iliac spine) (Macintosh and Bogduk, 1987), iliocostalis lumborum pars lumborum (ILL) (at the L4 level, midway between the lateral palpable border of the erector spinae and a vertical line through the posterosuperior iliac spine) (Macintosh and Bogduk, 1987). A reference electrode was placed on the acromion. Before the EMG recordings, the impedance between the recording electrodes and the reference electrode was checked to be less than 10 kΩ. A typical EMG recording during the Biering-Sørensen test can be seen in Fig. 3.

A three-dimensional ultrasound movement analysis system (Zebris CMS70P, Zebris Medical GmbH, Isny, Germany) and the accompanying WinData software were used to measure the spatial coordinates of ultrasonic markers that were placed on the skin overlying the spinous processes from L1 to L5, by means of double-sided adhesive patches. The data were collected at a sampling rate of 10 Hz. A detailed description of this measuring principle and the calculations is presented elsewhere (Kiss et al., 2004).

### 2.4. Signal processing and data analysis

#### 2.4.1. Endurance time based on objective movement analysis

A userwritten software algorithm was used to process the three-dimensional data in order to calculate the lumbar lordosis angles of the subjects throughout the test. Between three adjacent vertebrae an enclosed angle \( \alpha \) and supplementary angle \( \beta \) (180° − \( \alpha \)) could be determined. Because the lumbar segment consists of five vertebrae, three \( \beta \) angles can be defined. The lumbar lordosis (LL) was determined as the sum of these three \( \beta \) angles:

\[
LL = \sum_{i=1}^{4} \beta_i
\]

\( (i = \text{ith segment of three adjacent lumbar vertebrae}) \)

The mean value of the lumbar lordosis angles during the first 5 s of the test was used as a reference value. Afterwards, a 5-s window length ran throughout the sample to calculate the amount of times the lordosis angles differed more than 30% from that reference angle. This 30% level was based on preliminary tests where a suitable threshold value was determined to assess if a back extension was performed isometrically or not. The endpoint of the EMG signal was set when this 30% tolerance level was exceeded during more than three consecutive seconds. The procedure mentioned above thus provided an objective criterion to determine the endpoint of the EMG signal. The endurance time was calculated as the time difference between this endpoint and the beginning of the test. If the 30% level was not exceeded during the test, the whole EMG signal was used for further processing.

#### 2.4.2. Endurance time based on tactile feedback

Concerning the tactile feedback we have made use of a rope hung up between two vertical stands that was touching the
subjects’ seventh thoracic vertebra. The endurance time based on this method was determined as the time instant when the subject could not longer hold the testing position and contact between the subject’s seventh thoracic vertebra and the rope was lost.

2.4.3. Normalised median frequency slope (NMFslope)

Afterwards, each recorded EMG signal was divided in intervals of 1 s. The median frequency of the EMG power spectrum was calculated in each 1-s interval with fast Fourier transforms (FFT) using the Noraxon’s MyoResearch software v2.11 (Noraxon USA Inc., Scottsdale, AZ). The median frequency was defined as the frequency that divided the spectrum into two equal areas. Finally, linear regression analyses were performed on the calculated median frequencies as a function of time. The initial median frequency (MFinit) was defined as the intercept of the regression line and the median frequency slope (MFslope) was determined as the slope of the regression line. Because differences in subcutaneous tissue layers (between subjects and between muscle locations of the same subject) can affect the EMG parameters, MFslope was normalized by \( \frac{\text{MFslope}}{\text{MFinit}} \times 100 \).

2.5. Statistical analysis

A three-way analysis of variance with repeated measures design was conducted with the statistical software package SPSS v12.0 (SPSS Inc., Chicago, IL) to investigate the effect of the independent variables ‘muscle’ (eight muscles were measured), ‘side’ (left vs. right) and ‘gender’ (men vs. women) and their possible interaction effects on the dependent variable NMFslope. Post hoc pair-wise comparisons were made with Bonferroni corrections. Pearson correlation coefficients were calculated between NMFslope of the muscles and the endurance time, and between the muscle of each subject which demonstrated the greatest decline and the endurance time. Multiple stepwise linear regression analyses were performed to assess which NMFslope best predicted the endurance time. Furthermore, a two-way analysis of variance model with a repeated measures design was used to investigate the effect of the factors ‘muscle’ (eight muscles) and ‘method’ (method of objectively determining the test endpoint based on three-dimensional data of the lumbar vertebrae vs. test duration based on rope contact) and the possible interaction effect muscle × method on the NMFslope values. Pearson correlation coefficients
for each muscle were also calculated between NMF\textsubscript{slope} values obtained with the two methods. Statistical significance for all tests was accepted at the 5\% level.

3. Results

3.1. Differences in NMF\textsubscript{slope} values between muscles

The mean endurance time based on objective movement analysis (107.1 ± 43.8 s) was used in the following analyses: the three-way analysis of variance demonstrated no significant three-way interaction effect muscle × side × gender \((p = .250)\), and no significant two-way interaction effects (muscle × side: \(p = .603\); muscle × gender: \(p = .274\); side × gender: \(p = .704\)). Of the main effects, only the effect ‘muscle’ demonstrated significance \((p < .001)\). The main effects ‘side’ \((p = .753)\) and ‘gender’ \((p = .359)\) were not statistically significant. The mean NMF\textsubscript{slope} and standard deviations for each muscle are presented in Fig. 4. Significant and non-significant pair-wise comparisons of NMF\textsubscript{slope} between the back and hip muscles are shown in Table 1.

The multifidus muscle showed a significantly higher normalized MF\textsubscript{slope} \((p < .05)\) than all muscles, except the thoracic and lumbar part of the longissimus thoracis (all \(p > .05\)). For both the longissimus thoracis and iliocostalis lumborum muscles, the NMF\textsubscript{slope} was not significantly different between their thoracic and lumbar parts (all \(p > .05\)). The latissimus dorsi showed the lowest NMF\textsubscript{slope}, but not significantly different from ILT, GM and BF (all \(p > .05\)).

Of the hip muscles, the NMF\textsubscript{slope} was not significantly different between GM and BF (\(p > .05\)). Furthermore, both GM and BF were not significantly different from LD, ILT and ILL (all \(p > .05\)).

3.2. Correlation coefficients of NMF\textsubscript{slope} values and endurance time

The Pearson correlation coefficients between NMF\textsubscript{slope} parameters and the endurance time are shown in Table 2. For all muscles except LD significant correlation coefficients could be demonstrated, with \(r\) ranging from .467 to .710 (\(p < .05\)). The back muscles demonstrated higher correlation coefficients for the thoracic parts of the erector spinae (LTT and ILT) compared to the lumbar parts (LTL, ILL and MULT), although differences between these correlation coefficients were sometimes small (e.g. .633 for LTT vs. .614 for LTL). The hip extensor muscles (GM and BF) demonstrated lower correlation coefficients than the back muscles. The correlation coefficient between the greatest NMF\textsubscript{slope} of any of the subject’s muscles and endurance time was .685 (\(p < .05\)).

3.3. Which muscles predict test endurance time?

Multiple stepwise linear regression analyses, with all NMF\textsubscript{slope} values as independent variables and endurance

\begin{table}[h]
\centering
\caption{Pair-wise comparisons of NMF\textsubscript{slope} values (\(p\)-values after Bonferroni adjustments)}
\begin{tabular}{cccccccc}
\hline
Muscle & LD & LTT & LTL & ILT & ILL & MF & GM & BF \\
\hline
LD & \textless .001 & \textless .001 & .089 & .021 & \textless .001 & 1.000 & .921 & \text{} \\
LTT & 1.000 & \textless .001 & \textless .001 & 1.000 & \textless .001 & \textless .001 & 1.000 & \text{} \\
LTL & \textless .001 & \textless .001 & .361 & \textless .001 & \textless .001 & \text{} & \text{} & \text{} \\
ILT & 1.000 & \textless .001 & .367 & 1.000 & \text{} & \text{} & \text{} & \text{} \\
ILL & \textless .001 & .794 & .061 & \text{} & \text{} & \text{} & \text{} & \text{} \\
MF & \textless .001 & \textless .001 & \text{} & \text{} & \text{} & \text{} & \text{} & \text{} \\
GM & \text{} & \text{} & \text{} & \text{} & \text{} & \text{} & \text{} & \text{} \\
BF & 1.000 & \text{} & \text{} & \text{} & \text{} & \text{} & \text{} & \text{} \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Pearson correlation coefficients (\(r\)) between NMF\textsubscript{slope} values and endurance time}
\begin{tabular}{ll}
\hline
Muscle & Correlation coefficient (\(r\)) \\
\hline
LD & .182 \\
LTT & .633* \\
LTL & .614* \\
ILT & .710* \\
ILL & .548* \\
MULT & .621* \\
GM & .467* \\
BF & .480* \\
GREATEST & .685* \\
\hline
\end{tabular}
\end{table}

LD = latissimus dorsi, LTT = longissimus thoracis pars thoracis, LTL = longissimus thoracis pars lumborum, ILT = iliocostalis lumborum pars thoracis, ILL = iliocostalis lumborum pars lumborum, MULT = multifidus, GM = gluteus maximus and BF = biceps femoris. The error bars indicate the standard deviations.

Fig. 4. Normalized MF\textsubscript{slope} values (%/s) of the eight back and hip muscles obtained with the “objective” method (i.e. using endurance time based on objective movement analysis) and the “original” method (i.e. endurance time based on tactile feedback) (LD = latissimus dorsi, LTT = longissimus thoracis pars thoracis, LTL = longissimus thoracis pars lumborum, ILT = iliocostalis thoracis pars thoracis, ILL = iliocostalis lumborum pars thoracis, MULT = multifidus, GM = gluteus maximus and BF = biceps femoris. The error bars indicate the standard deviations).
Table 3
Pearson correlation coefficients (r) of NMF_slope values between the two methods

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Correlation coefficient (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD</td>
<td>.962*</td>
</tr>
<tr>
<td>LTT</td>
<td>.974*</td>
</tr>
<tr>
<td>LTL</td>
<td>.961*</td>
</tr>
<tr>
<td>ILL</td>
<td>.980*</td>
</tr>
<tr>
<td>III</td>
<td>.982*</td>
</tr>
<tr>
<td>MULT</td>
<td>.946*</td>
</tr>
<tr>
<td>GM</td>
<td>.978*</td>
</tr>
<tr>
<td>BF</td>
<td>.936*</td>
</tr>
</tbody>
</table>

LD = latissimus dorsi, LTT = longissimus thoracis pars thoracis, LTL = longissimus thoracis pars lumbarum, ILL = iliocostalis lumbarum pars thoracis, III = iliocostalis lumbarum pars lumborum, MULT = multifidus, GM = gluteus maximus and BF = biceps femoris. * p < .01.

The statistical analysis revealed that endurance time could be significantly predicted only by NMF_slope of the ILT (p < .001). The resulting regression equation could be written as:

\[
\text{endurance time} = 159.5 + 212.3 \times \text{NMF}_{\text{slope}} \text{ of the ILT}
\]

\[p < .001, \text{ adjusted } R^2 = .477\]

### 3.4. Comparison of both methods

The method of objectively determining the endpoint of the test based on three-dimensional data of the lumbar vertebrae yielded significantly lower endurance times vs. the method based on rope contact (107.1 ± 43.8 s vs. 123.5 ± 49.8 s, \(p = .022\), respectively). The differences in NMF_slope values between the two methods are presented in Fig. 4. The statistical analysis revealed that the interaction effect muscle × method was not significant \((p = .326)\). Significant differences could be demonstrated between both methods \((p = .024)\) and between the muscles \((p < .001)\) in NMF_slope values. The method of objectively determining the test endurance time – based on the three-dimensional movement analyses of the lumbar vertebrae – yields significantly higher fatigue rates, with the average percentage difference between the two methods being 4.2%. The correlation coefficients of NMF_slope values for each muscle between the two methods are presented in Table 3. These results demonstrated high correlation coefficients for all muscles between the two methods \((r\) ranging from .936 to .982, all \(p < .01)\).

### 4. Discussion

The results of the present study showed significant differences in median frequency slopes between several back and hip muscles during a modified Biering-Sørensen test. Because bipolar surface EMG recordings from several muscles were measured to investigate the EMG power spectra, crosstalk (i.e. signal detected over a muscle but generated by another muscle close to the first one (Merletti and Parker, 2004)) may have influenced the results in the current study. In literature, different opinions exist whether surface electromyographic measurements are suitable for measuring multifidus muscle activity. Arokoski et al. argumented that surface EMG measurements may be used in the assessment of multifidus muscle function (Arokoski et al., 2002), whereas Stokes et al. concluded that measurements of the multifidus muscle activity requires intra-muscular recording (Stokes et al., 2003). In the current study, the electrode locations of the several muscles were accurately determined – based on anatomical studies – and the guidelines of the SENIAM project were followed in electrode placements and – configuration (Hermens et al., 1999). The presence of crosstalk is however inherently associated with surface EMG recordings and certainly in a study like this where multiple muscle locations close to each other were measured. Even if great care was taken as mentioned above, crosstalk cannot be ruled out.

#### 4.1. Median frequency characteristics of back and hip muscles

The first aim of the present research study was to assess the differences in NMF_slope values between back and hip muscles. The latissimus dorsi showed the least rapid decline of the median frequency of the back muscles, which can be explained by their stabilizing role of the trunk when forces are applied in the frontal plane. Since the modified Biering-Sørensen test requires trunk muscle activity to overcome the force of gravity in the sagittal plane, little demand of the latissimus dorsi muscles may be expected. The multifidus muscles had the greatest decline in median frequency, and the iliocostalis lumbarum muscles showed lower NMF_slope than multifidus and longissimus thoracis. Based on the research by MacIntosh and Bogduk (1987) the four distinct parts of the erector spinae were studied. The lumbar parts of both muscles showed slightly higher NMF_slope values than their thoracic counterparts (although the differences in NMF_slope values were not significant). Similar findings have been reported in other studies (Mannion and Dolan, 1994; Ng and Richardson, 1996; Ng et al., 1997). The results of the present study also showed that the more medial muscles of the erector spinae (longissimus thoracis) showed higher values of NMF_slope than the more lateral muscles (iliocostalis lumbarum), which is in agreement with the study of Sparto et al. (1997).

The differences in EMG median frequency slopes between the various muscles can be explained by a number of factors, such as differences in fiber-type characteristics (Mannion and Dolan, 1994; Mannion et al., 1998), – in activation levels during the test (Ng and Richardson, 1996; Tan et al., 1993; Vink et al., 1988), – in the load the muscles experience (Sparto et al., 1997), – in muscle length throughout the test (Mannion and Dolan, 1994, 1996), and – in moment arms between muscles. A less rapid decline of median frequency during the Biering-Sørensen
test will be demonstrated by muscles having a greater relative area of type I fibers, by muscles demonstrating a lower activation level during the test, by more cephalad back muscles and by muscles having a greater moment arm.

Concerning the results of the hip extensors in the present study, clear fatigue of the gluteus maximus and biceps femoris was demonstrated with similar values of NMF slope as demonstrated in the study of Kankaanpää et al. (1998). Lower NMF slope values were however demonstrated in other studies (Plamondon et al., 2004; Sparto et al., 1997), possibly due to differences in study protocol (e.g. the use of intermittent prone back extensions in Plamondon et al. (2004) vs. isometric contractions in the present study).

4.2. Is the Biering-Sørensen test a valid test for measuring back muscle fatigue?

The second aim of the present study was to assess which muscles limit performance in terms of test endurance time, in order to determine whether the Biering-Sørensen test is a valid determinant for evaluating back muscle fatigability. Therefore, correlation coefficients between NMF slope values and endurance time were calculated, and a multiple stepwise linear regression was performed. The results showed generally low to moderate correlation coefficients between NMF slope and the endurance time for all muscles except the latissimus dorsi, with $r$ ranging from .467 to .710 ($p < .05$). The results of the present study indicated higher correlation coefficients for the thoracic parts of the lumbar erector spinae compared to the lumbar parts. However, care has to be taken when comparing correlation coefficients because differences were sometimes very small (e.g. $r = .633$ for the thoracic part of the longissimus thoracis vs. $r = .614$ for the lumbar part of the longissimus thoracis) and the variability in the measures may be greater than the actual differences. One possibility to assess the issue mentioned above is to repeat the experiments and evaluate if the differences persist. Another option is to compare the present results with studies in the literature. The finding of the present study mentioned above is in agreement with Kankaanpää et al. (1998) and opposite to Mannion and Dolan (1994), who demonstrated higher correlation coefficients for the lumbar region. The latter study however showed that the highest correlation coefficient was given when the greater NMF slope was selected at either of the two levels (Mannion and Dolan, 1994). This was not confirmed in our study, as the correlation coefficient of the iliocostalis lumbarum pars thoracis ($r = .710$) was higher than the greatest NMF slope of any of the muscles measured ($r = .685$). The results of the present study also showed that the hip extensor muscles demonstrated lower correlation coefficients than the back muscles, which is in agreement with the study of Kankaanpää et al. (1998). Overall, Kankaanpää et al. (1998) demonstrated higher correlation coefficients for back as well as hip muscles compared to the results of the current study, which may be explained by the significant differences in endurance times ($191.7 ± 55.6$ s in the study of Kankaanpää et al. (1998) vs. $107.1 ± 43.8$ s in the present study, $p < .001$). The use of an objective criterion which determined the endurance time according to an algorithm based on the subject’s lumbar lordosis throughout the test, may explain the lower endurance times in the present study. Investigating which NMF slope best predicted the endurance time, the multiple stepwise linear regression demonstrated that – of all measured back and hip muscles – only NMF slope of the thoracic part of the iliocostalis lumborum muscle could significantly predict the endurance time. The finding that muscle fatigue of the hip extensor muscles cannot explain the test endurance time supports the validity of the Biering-Sørensen test for measuring back muscle fatigue. Contrary to the results of Mannion and Dolan (1994), who concluded that the most fatigable muscle best predicted the endurance time during the Biering-Sørensen test, the results of the present study indicate that the best prediction was given by one of the muscles that was the least fatigued. We do not have a direct explanation for this controversy, except that Mannion and Dolan have measured the EMG activity at Th10 and L3, whereas we have measured the EMG activity of several back muscles (between L1 and L5 level). Although Kankaanpää et al. (1998) demonstrated similar results with regard to the correlation coefficients between NMF slope and endurance time to the present study, the authors have not performed regression analyses to investigate which of their NMF slope predicted endurance time, and therefore no comparisons with the present study nor with the study of Mannion and Dolan (1994) can be made.

4.3. Difference between the two methods for determining test endurance time

The third aim of the current study was to standardise as much as possible the Biering-Sørensen test. We have made use of both verbal and tactile feedback, as well as an objective criterion (based on three-dimensional movement analysis of the lumbar vertebrae) to determine the endpoint of the test. Stevens et al. have employed the same methodology of tactile feedback in order to determine the test endurance time of the Biering-Sørensen test, and demonstrated good reliability (Stevens et al., 2006). Similar tactile feedback was also used in the study of Koumantakis et al. (2001). When comparing both methods in our study to determine the test endurance time of the Biering-Sørensen test (rope contact as determination of test vs. determination based on three-dimensional movement analysis data of the lumbar vertebrae), an important finding is that the two methods are significantly different in yielding NMF slope values, but highly correlated. The high correlation coefficients between the two methods imply that both methods can be used. The easier method (without using the three-dimensional movement
analyses) with the rope contact at Th7 thus can be considered a good method to use ‘in the field’. This finding is supported by the fact that the average percentage difference between the two methods was only 4.2%, although the differences were statistically significant. However, further research (e.g. reliability studies) is necessary in order to assess if these differences persist.

5. Conclusion

In conclusion, significant differences in median frequency slope parameters could be demonstrated between several back and hip muscles during a modified Biering-Sørensen test. Low to moderate correlation coefficients could be shown between NMF slope values of the back and hip muscles and endurance time. Overall, an important clinical conclusion based on the results of the present study is that, although back as well as hip muscles fatigued during the test and their NMF slope values were significantly correlated with the endurance time, only the thoracic part of the iliocostalis lumborum muscle ultimately seemed to be responsible for limiting performance in terms of endurance time during a modified Biering-Sørensen test. This supports the validity of the Biering-Sørensen test for measuring back muscle fatigue. Because significant differences in back muscle fatigue have been demonstrated between healthy subjects and patients with low back pain, the results of this study cannot be extrapolated to a low back pain patient group. Further research is necessary to investigate which muscles of patients with low back pain limit the test endurance time of the Biering-Sørensen test.

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