Prediction of Maximal Surface Electromyographically Based Voluntary Contractions of Erector Spinae Muscles From Sonographic Measurements During Isometric Contractions

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Objectives—Currently, there are no studies combining electromyography (EMG) and sonography to estimate the absolute and relative strength values of erector spinae (ES) muscles in healthy individuals. The purpose of this study was to establish whether the maximum voluntary contraction (MVC) of the ES during isometric contractions could be predicted from the changes in surface EMG as well as in fiber pennation and thickness as measured by sonography.

Methods—Thirty healthy adults performed 3 isometric extensions at 45° from the vertical to calculate the MVC force. Contractions at 33% and 100% of the MVC force were then used during sonographic and EMG recordings. These measurements were used to observe the architecture and function of the muscles during contraction. Statistical analysis was performed using bivariate regression and regression equations.

Results—The slope for each regression equation was statistically significant \( (P < .001) \) with \( R^2 \) values of 0.837 and 0.986 for the right and left ES, respectively. The standard error estimate between the sonographic measurements and the regression-estimated pennation angles for the right and left ES were 0.10 and 0.02, respectively.

Conclusions—Erector spinae muscle activation can be predicted from the changes in fiber pennation during isometric contractions at 33% and 100% of the MVC force. These findings could be essential for developing a regression equation that could estimate the level of muscle activation from changes in the muscle architecture.

Key Words—electromyography; musculoskeletal ultrasound; regression analysis; sonography; spine
The ability to obtain quantitative estimates of muscle forces during movement has considerable clinical potential. Registration of these objective and quantitative variables allows not only monitoring of the evaluation process but also quantification of normograms to prevent people at high risk from having musculoskeletal disorders. In addition, computational modeling of the musculoskeletal system could provide qualitative and quantitative information on the musculoskeletal system and information on the dynamics of the movement. Previous studies demonstrated applicability in rehabilitation procedures in the noninvasive estimation of individual muscle forces and in the study of control strategies for the coordination of movements.

The erector spinae (ES) muscles are mainly responsible for lumbar extension; they also contribute to maintaining the position, as well as to the rotation and lateral bending, of the trunk. Sonography is useful for developing musculoskeletal models, as it shows the changes that take place in muscle morphologic characteristics during contraction. Surface electromyography (EMG) is frequently used to estimate the degree of muscle activation. To our knowledge, there are no studies that have combined sonography with EMG to estimate the absolute and relative strength values of the ES muscle in healthy individuals. Thus, the aims of this study were to calculate the correlation between architectural and functional variables during maximum and 33% isometric contractions in healthy adults of both sexes, aged 18 to 65 years, were recruited. The exclusion criteria were the presence of musculoskeletal or neurologic disorders, a history of spinal or hip surgery, pregnancy, cancer, osteoporosis, and an inability to perform the lumbar extensions required during the trial.

All participants provided written informed consent before participation, and the study was approved by the Human Subjects Review Board of the University of Malaga, in accordance with the requirements of the 2009 Declaration of Helsinki.

**Procedure**

**Recording of the Maximal Isometric Force**

The maximum isometric force was recorded by a load cell (RealPower, Globus, Italy) located between two strings: one was attached to the wall and the other to a precalibrated lumbar extension machine, on which the extensions were performed. The angles created between the load cell and horizontal and between the chain and the thrust direction were 0°.

**Electromyography**

A bipolar surface EMG system (DataLOG; Biometrics, Ltd, Newport, England) with two electrode sensors separated by 1 cm was used. The skin sensors were fixed to the skin by an adhesive that left the electrodes free. The sampling frequency of the Biodex (Biometrics Ltd, Newport, England) was set at 1000 Hz.

The sensors were placed at the L3–L4 level, 3 cm from the line created by the spinous process, bilaterally on both ES muscle bellies. Measurement of the ES was chosen at this level because it is the point of the center of the muscle belly of the ES (lumbar portion). Before the sensors were placed on the back of each participant, the skin was cleaned with alcohol.

Electromyographic values were calculated from the difference between the maximum and minimum recordings. Before this calculation, all recorded signals were passed through a low-pass filter. The acquisition of values and treatment records was managed by DataLink version 3.0 software (DataLOG; Biometrics Ltd; Figure 1).

**Sonographic Recording**

Sonograms of the ES were obtained with a SonoSite Titan system with an 8.5-MHz linear transducer (FUJIFILM-SonoSite, Bothell, WA). The transducer (5 cm wide) was placed immediately below the EMG sensors in a longitudinal direction with respect to the direction of the ES muscle fibers. The depth of the image was 6.5 cm for all participants.

Sonography has been shown to have moderate to excellent reliability for paraspinous musculature measurements, with intraclass correlation values ranging between 0.72 and 0.98. This tool has the disadvantage of relying on the skill of the operator for taking measurements. However, one study showed that the interobserver reliability ranged between 0.900 and 0.948, whereas the intraobserver values ranged from 0.938 to 0.962.

A bilateral sonogram was captured during each isometric contraction performed. Two variables of muscle architecture (thickness and pennation angle) were obtained from the sonograms via ImageJ software.
The muscular thickness measurement was the distance between the surface and deep aponeurosis of the muscle. The pennation angle was calculated by measuring the angle between the deep aponeurosis and muscle fiber when it passed through the center of the muscle. During this process, the researcher was blinded, so he did not know the participant’s identity of each sonogram. An example of a processed sonogram is shown in Figure 2.

**Experimental Protocol**

Each participant was placed on the machine (Figure 3) and made the first attempt with no resistance to find the pushing position that was most comfortable. Next, the maximum isometric strength was measured through the load cell placed between the two strings, as previously explained. The movement was blocked when the participant reached an extension of 45° from vertical (measured with an inclinometer; Figure 3). The participant executed 3 repetitions of 5 seconds, with a rest period of 90 seconds between each repetition. The highest peak force was recorded. Once all 3 attempts had been executed, the maximum value was obtained, which was considered the 100% isometric maximum strength value, from which the 33% force value was calculated.

Two trials (33% and 100% of the MVC force) were undertaken for ES muscle recordings while simultaneously recording the EMG, torque, and sonogram. Five seconds of data was collected for each trial to ensure that the joint moment had reached a plateau before the sonogram was saved. Two trials were performed, with 90 seconds of rest between each. The pennation angle and the EMG for the two trials were averaged. An EMG recording and a bilateral sonogram of the ES were taken.

After the sonograms and muscle activation levels were obtained using sonography and surface EMG, respectively, the variables (pennation angle, thickness, and MVC) were measured as previously described. These parameters were used for a bivariate correlation to develop the regression equation from which the relationship between the architectural and functional variables of the ES could be determined.

The pennation angles estimated using the regression equations were plotted relative to the pennation angles measured with sonography. In addition, we calculated regression equations using participant-specific EMG and average values of the pennation angles at 33% and 100% of the MVC. This process was done to evaluate the efficacy of the equations when participant-specific pennation angles at 33% and 100% were not available.

**Figure 1** Example of an MVC graphic.

**Figure 2** Example of the architecture variables measured from the sonogram. A indicates pennation angle, and T, muscle thickness.

**Figure 3** Representation of the precalibrated system used during the study.
All statistical analyses were performed with SPSS version 17.0 software (IBM Corporation, Armonk, NY).

Results

Table 1 shows the mean anthropometric data of the participants by sex. Table 2 shows the mean values of each variable. Figure 4 shows an example of the linear correlation between the ES EMG and the pennation angle for the left side. It is important to note that the slope and fit of the line varied from participant to participant because of interparticipant variability and differences in the pennation angles between the left and right sides (Table 3). For these reasons, pennation angles at 33% and 100% of the MVC were included in the analysis so that participant-specific values could be predicted for participants with a similar normalized EMG.

The magnitude of the difference between the linear regression of the pennation angles and the values measured by sonography for all participants is illustrated in Figure 5. The scattering of data points around the diagonal line shows the magnitude of the error. The slope for each regression equation was statistically significant (P < .001) with R² values of 0.837 and 0.986 for the right and left ES (Table 3), respectively. The standard error estimates between the sonographic measurement and the regression of the estimated pennation angle for the right and left ES were 0.10 and 0.02, respectively. Table 4 shows the correlation values between the sonographic and EMG results.

Discussion

To the best of our knowledge, this study is the first to determine the level of muscle activation from changes in the pennation angle of the ES muscles during isometric contractions at different intensities. Contractile effort is reflected by the magnitude of the changes in the EMG recording, pen, pennation angle, and muscle fiber length with increasing muscle contraction intensity. Therefore, EMG signals could predict changes in the fiber length and pennation angle. The overall finding from our study was that the relationship between the EMG recording and pennation angle was fairly linear and statistically significant for muscles tested on both sides (R², right, 0.915; left, 0.993; P < .001) when pennation angles at 33% and 100% of the MVC were included in the analysis. On the basis of the results obtained, we could say that the main objective of the study and the hypothesis were confirmed. It is possible to appreciate the existence of a bivariate correlation between the pennation angle and activity level in the ES muscles. From this correlation, it is possible to establish the regression equation to predict the level of muscle activation during isometric contractions close to the optimal length of the muscle fiber from the changes in the pennation angle of the ES muscle.

Table 1. Mean Descriptive Variables of the Participants

<table>
<thead>
<tr>
<th>Variable</th>
<th>Women</th>
<th>Men</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Age, y</td>
<td>36.89 ± 15.41</td>
<td>36.89 ± 12.22</td>
</tr>
<tr>
<td>Height, cm</td>
<td>178.14 ± 6.74</td>
<td>165.78 ± 5.24</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>78.6 ± 14.35</td>
<td>57.9 ± 6.68</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>24.46 ± 3.01</td>
<td>21.06 ± 2.76</td>
</tr>
</tbody>
</table>

Data are presented as mean ± SD. BMI indicates body mass index.

Table 2. Mean Values of the Measured Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Intensity, %</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight moved, kg</td>
<td>62.7 ± 23.47</td>
<td>58.54 ± 22.10</td>
<td>20.53 ± 791</td>
</tr>
<tr>
<td>Torque, N/m</td>
<td>100</td>
<td>58.54 ± 22.10</td>
<td>20.53 ± 791</td>
</tr>
<tr>
<td>Angle, °</td>
<td>100</td>
<td>6.50 ± 2.42</td>
<td>5.10 ± 2.28</td>
</tr>
<tr>
<td>Thickness, m</td>
<td>100</td>
<td>0.030 ± 0.004</td>
<td>0.031 ± 0.006</td>
</tr>
<tr>
<td>MVC, mV</td>
<td>100</td>
<td>503.40 ± 197.82</td>
<td>586.00 ± 262.47</td>
</tr>
</tbody>
</table>

Data are presented as mean ± SD.

Table 3. Slope for Each Regression Equation

<table>
<thead>
<tr>
<th>Model Summary</th>
<th>R</th>
<th>R²</th>
<th>Adjusted R²</th>
<th>SE of Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>0.915</td>
<td>0.837</td>
<td>0.816</td>
<td>0.104</td>
</tr>
<tr>
<td>Left</td>
<td>0.993</td>
<td>0.986</td>
<td>0.984</td>
<td>0.027</td>
</tr>
</tbody>
</table>

*aP < .001.
In line with statements by Manal et al.\textsuperscript{15} the correlation between surface EMG and a pitch of less than 20% of the MVC is irrelevant because the pennation angle of the ES is small; therefore, even a relatively large change of several degrees will have a negligible effect on the resulting force. On the other hand, while maintaining the modeling-based perspective, Manal et al.\textsuperscript{15} recommended investigating the muscles that are predominant during movement. In the lumbar area, the main muscle that contracts is the ES\textsuperscript{22}; therefore, determining the correlation between the angle and surface EMG of this muscle may have greater clinical importance than that of any other muscles involved in such a movement. The correlation between the pennation angle and the surface EMG area on the right and left ES had a high $R^2$ value of 0.8 (0.915 and 0.993, respectively) at a significance level of $P < .001$, showing that greater than 80% of the variance in the pennation angle could be explained by standard EMG and the angle of tilt for both sides.

It takes a long time to record the pennation angle over a wide range of intensities and contractions of various muscles. The ability to predict the EMG pennation angle has several practical applications. A description of the function and muscle architecture using sonography and EMG has been performed in different regions of the body: arm,\textsuperscript{12} ankle,\textsuperscript{15} leg,\textsuperscript{16} and abdominal muscles.\textsuperscript{7} The data extracted from these studies could be useful for planning rehabilitation protocols in people with acute or chronic musculoskeletal disorders. A study has shown the effectiveness of this kind of analysis for planning intervention strategies in people who had strokes.\textsuperscript{7} The analysis of the function and muscular architecture of the ES, the most important muscle to stabilize and mobilize the lumbar spine,\textsuperscript{9} may be useful for the assessment and monitoring of personal rehabilitation protocols in patients with low back pain. It could also help monitor people with a higher risk of musculoskeletal disease (ie, older\textsuperscript{23} and obese\textsuperscript{24}), to plan prevention strategies. The pennation angle was the most important architectural variable analyzed in this study, as it has been directly correlated with muscle functional capacities (such as force and moment of force).\textsuperscript{25}

This study was limited by the fact that the feasibility of using regression equations in dynamic contractions is not entirely clear because it is necessary to consider changes in the various joints throughout the whole range of motion. Moreover, a validation test has to be performed to confirm the correlation between variables with many angles of movement.\textsuperscript{12} Another limitation could be the reliance on the skill of the operator, a factor that helps reduce excessive noise (particularly common at levels <20% of the MVC) when undertaking EMG.\textsuperscript{12} However, it is clear that there was a strong correlation between the pennation angle of the ES and muscle activity measured by surface EMG. The results would have gained strength if a second researcher had also made an analysis of the sonograms, reducing the degree of measurement error and allowing an analysis of interobserver reliability.

Sonography was used to measure the pennation angle and establish its correlation with the level of muscle activation by referring to the maximum isometric muscle strength; we observed that their changes depended on the intensity of muscle contraction. Therefore, one of the points to be taken from this study is the need to simultaneously use tools that provide associations and predictions to determine the correlation between architecture and function in current and future biomechanical models.

In conclusion, this study enabled the in vivo measurement of ES muscles via two noninvasive methods (sonography and EMG) and constructed a model that could demonstrate changes in muscle contraction on the basis of moderate-intensity (33%) and maximum-intensity (100%) MVC. Using both intensities, we obtained a bivariate correlation that was essential for developing a regression equation that could estimate the level of muscle activation from changes in the pennation angle.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>100% MVC Right</th>
<th>100% MVC Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMG 100% right</td>
<td>0.915\textsuperscript{a}</td>
<td>0.638</td>
</tr>
<tr>
<td>EMG 100% left</td>
<td>0.732</td>
<td>0.993\textsuperscript{a}</td>
</tr>
</tbody>
</table>

\textsuperscript{a}$P < .001$.  

Figure 5. Linear regression of the pennation angles and the values measured by sonography for all participants.
References


