ARE LOWER LIMB ELECTROMYOGRAM PROFILES SYMMETRICAL DURING A BARBELL SQUAT? (A CASE STUDY)

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Abstract

Aim. The action of the central nervous system that controls neuromuscular functions are reflected by electromyogram (EMG) profiles of muscle activity of those which are basic. However, there seems to be a relationship between the EMG profiles and movement patterns (e.g., values of lower limb joint angles). We would like to find out how EMG profiles and movement patterns changes during the squat movement with increasing loads, and especially, to determine the degree of symmetry of selected homologous muscles. Due to the lack of critical information addressing symmetry, we studied the EMG profiles of six homologous leg muscles (i.e. tibialis anterior, gastrocnemius, rectus femoris, biceps femoris, gluteus maximus and erector spinae) during the squat movement depending on load size.

Basic procedures. For this purpose, we checked the usefulness of the multimodal measuring system (SMART-E, BTS). The system consisted of 6 infrared cameras (120 Hz) and a wireless module to measure muscle bioelectric activity (Pocket EMG). The Smart Analyser software was used to create a database allowing the chosen EMG profiles and movement patterns to be compared. Eleven healthy men participated in this study; however, two were selected for analysis. The first of subject was 36 years old (body mass 82 kg; body height 180 cm; 1RM in full squat 140 kg). The second was 28 years old (body mass 90 kg; body height 183 cm; 1RM in full squat 110 kg).

Results and main findings. The subjects performed consecutive sets of a single repetition of the full squat with increasing load (70, 80, 90 and 100% 1RM of the anticipated maximum weight) until the appointment of one maximum repetition. For analysis, however, only samples with moderate and maximal loads (70% and 100% 1RM, respectively) were selected.

Conclusions. The mean of the absolute values regarding differences in the amplitude magnitudes of individual pairs of homologous muscles was taken as a measure of symmetry of the EMG profile. The load increase during the squat contributed to an increase in profile asymmetry of the lower limb homologous muscles pairs. The slightly lesser asymmetry may have caused worsening movement fluidity.

1. Introduction

Subjects of trails in which a squat with maximum load is performed often show changed motor patterns compared to those trials with moderate loads. Such altered patterns have also been demonstrated, for example, in people with anterior cruciate ligament injury during gait, functional movements and regular rehabilitative exercises [1-3]. This may be partly due to temporary sensorimotor disturbances. The action of the central nervous system, controlling neuromuscular functions, reflects the profiles of electrical activity of major muscle contractions (elec-
tremograms – EMG), in this case, of the lower limbs. Thus, it seems that there should be a connection between EMG profiles and motor patterns.

According to Yang and Winter [4], “... movement is the effect of interactions between muscle tension, controlled by the central nervous system, and mechanical requirements of the motor task”. An understanding of how the nervous system responds to changes related to the mechanical requirements of the task is necessary to understand motor control. The mechanical requirements of a squat with an increasing load vary considerably. For this reason, they can be a good example in examining the relationship between these requirements and the behaviour of the nervous system.

The electrical activity of a muscle is a reflection of both the exit from the neuron terminals (from the nervous system) and the entry into the mechanical system. Hence, the size of EMG amplitudes and their course over time can provide information on both of these systems. Changes in EMG amplitudes during a barbell squat were examined by, among others, Gullett et al. [5] and Contreras et al. [6], but they presented only the results of the global measurement – average EMG for all phases: descent and ascent. Such a global measure could mask significant differences in EMG at particular phases. Therefore, there is a real need to more accurately determine EMG changes in squats with different loads, both in terms of size of the amplitude and time of their occurrence.

In order to determine whether the EMG profile of a given limb is appropriate, it should be compared with some control, for example the opposite limb, or with the profile of a specific population. The opposite limb is a potentially valuable control, because it is possible to avoid population variables as well as others (e.g. squat speed). However, to ensure that the given homologous muscle profiles are actually different, their symmetry/asymmetry should be quantified.

Robertson et al. [7] presented EMG linear envelopes as profiles of muscle activity during the entire squatting movement, which were normalized for the maximum contractions of each subject, but did not raise the issue of symmetry. In another article, Yavuz and Erdag [8] did the same, presenting EMG profiles as the average electrical activity of selected muscles at constant time intervals. However, Arsenault et al. [9] had already paid particular attention to the problem of symmetry when they showed the high correlation between shapes of entire courses of previously straightened and filtered EMG signals for the homologous rectus femoris and soleus muscles in adults during gait. In the opinion of Öunpuu and Winter [10], while aggregate data (e.g. global mean values for entire characteristics [11]) reflect proper symmetry based on statistical analysis, they cover up the asymmetry of individuals. In addition, by presenting data on the movement of a single individual, it is possible to identify such elements of movement technique (i.e. motor pattern) that are associated with achieving better results [12-13].

Due to the lack of critical information on symmetry, we examined EMG signals of six homologous lower limb muscles when squatting with a barbell. We would like to learn how EMG profiles and squat movement patterns change along with a change in load, and to determine the degree of symmetry/asymmetry of six selected homologous muscles.

2. Material and methods

2.1. Characteristics of the subjects

This work is a fragment of a doctoral dissertation in preparation. Eleven healthy men recreationally performing strength exercises voluntarily participated in the research conducted at the Biomechanics Department of Jerzy Kukuczka University of Physical Education in Katowice. However, since the evaluation and improvement of the technique (way of performing) sports activities always refer to a specific person, the work presents the characteristics of symmetry of homologous muscles and the motor pattern for two exemplary representatives of strength sports. The first of the subjects is 36-year-old A.M., who has 15 years of training experience, weighs 82 kg and is 180 cm tall. The second is 28-year-old R.N, with 4 years training experience, weight 90 kg and height 183 cm. Approval of the University Bioethics Committee for Scientific Research at the Jerzy Kukuczka University of Physical Education in Katowice was obtained.

2.2. Research protocol and procedures

In the measurement session, the subjects squatted with a barbell of increasing weight until establishing one maximal repetition – 1RM. In the case of A.M., the weights of the lifted bar was 100, 115, 130 and 140 kg, respectively, and R.N., 80, 90, 100 and 110 kg, respectively. Only the samples of extreme loads (70 and 100% 1RM, i.e. 100 and 140 kg respectively for the first and 80 and 110 kg respectively for the second one) were selected for the analysis.

The research involved squatting with the “free” barbell, held in back of the shoulders. In baseline position, the subjects set their feet to the width of their shoulders, with the toes turned slightly outwards. The squatting movements started from an upright position, by bending in the hip, knee and ankle joints, then shifting to the lowest lower position. After reaching the desired depth of the squat, the subjects raised themselves back to an upright position. The lumbar spine was kept in a neutral position throughout the entire ascent period, and the
trunk remained in an almost vertical position at this time. The feet of the subjects were stably and firmly placed on the ground so that during the entire squatting movement, their whole sole adhered to the surface. At the appropriate depth of the squat, the thighs slightly crossed the line parallel to the ground, at which time the hip and knee joints were greatly bent. The subjects squatted with the barbell in a calm, controlled manner, to the lowest position (descent phase), and then without stopping, smoothly and quickly raised up to full extension of the knee and hip joints (ascent phase). Two strong individuals with several years of experience in resistance training, secured (delayed) the subjects in the case of a potentially incorrect attempt.

2.3. Registration of parameters

To record the parameters of the athlete and barbell movement, while squatting with the barbell on the shoulders, the Smart-E measuring system (BTS, Italy) was used, which was simultaneously programmed for multidimensional motion analysis. In short, the system consists of six infrared cameras and a wireless module for measuring the bioelectric activity of Pocket EMG muscles. In addition, the Kistler 9182C force platform (KISTLER, Switzerland) was used. Electrical activity was recorded using surface electrodes for muscles on both sides of the body (homologous): *tibialis anterior* (TA), the medial part of *gastrocnemius medialis* (GMed), the long head of the *biceps femoris* (BF), *rectus femoris* (RF), *gluteus maximus* (GMax) and the lumbar section of *erector spinae* (ES). The electrodes were placed above the sites of muscle motor activity, in accordance with the European SENIAM recommendations for surface electromyography [14]. A full description of the used measurement tools and procedures as well as methods of processing the obtained signals were presented in earlier works as part of the cyclic Seminars of Sport Biomechanics and Rehabilitation [12-13, 15-16]. This modern system allows analysis of motion based on comprehensive image registration of motor function technique (here a squat), including the measurement of kinematic and kinetic parameters (external motion structure [17]) as well as bioelectric activity of the muscles at work (internal structure). All measurements, and thus obtained characteristics, were temporarily synchronized by using a main processor. The research material collected in this way will be thoroughly analysed in the preparation of the doctoral dissertation. In this work, the EMG profiles of only selected muscles were analysed, as well as the characteristics of angles in the knee joints (motor patterns) of the two participants examined, which are the subject of our current research.

2.4. EMG data reduction and testing procedure

The raw EMG signal was filtered (Butterworth filter band 20-250 Hz), straightened and smoothed using the root-mean-square (RMS) method with a 100 ms mobile window. The mean value was calculated from RMS EMG in millivolts, separately for the descending and ascending phases of each barbell squat. For this purpose, the Smart Analyzer programme (BTS, Italy) was used. In order to compare the activity between homologous (compatible) muscles and obtain biologically important data, normalization of maximal voluntary contractions (MVC) was performed for each muscle, in accordance with the procedures described by Konrad [18]. Measurements of the 3-second maximal contraction of each muscle were performed in static conditions, and the intervals between them were 1 minute long. EMG [% MVC] data for all muscles were divided into descending and ascending phases.

In order to determine the degree of symmetry of homologous muscles, the modulus (absolute value) of differences in normalized EMG values between the pair of homologous muscles at 100 time-normalized points was calculated first. These data were then averaged for the whole squatting movement and for each phase separately. Thus, the symmetry degree of the EMG profiles was determined by means of two measures: the mean of modules of amplitude differences between individual pairs of homologous muscles for the squatting movement (MMAD) and the mean for two phases of movement calculated in the same way (descent – MMAD, and ascent – MMAD, respectively). A larger value of these measures indicates lower symmetry of the EMG profiles of the compared muscles, and vice versa, the smaller value indicates greater symmetry. All calculations were performed using an Excel spread-sheet.

3. Results

Assuming MMAD, MMAD, and MMAD, as a measure of homologous muscle symmetry was justified due to the great similarity of the EMG profile shape in particular muscle pairs (Fig. 1 and 2).

The calculated MMAD measurement values for particular homologous muscle pairs in trials with the 70 and 100% 1RM loads are presented in Tab. 1 and 2.
Figure 1. EMG profiles normalized according to amplitude and time [% MVC] for three pairs of homologous lower limb muscles (TB – tibialis anterior, GMed – gastrocnemius mediale, RF – rectus femoris) of subject A.M.. Attempts at squat movement (during the descent and ascent phases) were performed with the following loads: A) 70% 1RM and B) 100% 1RM.

Table 1. Mean of modules of amplitude differences – MMAD [% MVC] for the pairs of homologous muscles of lower extremities of A.M. subject. Attempts of squat movement were performed with a 70 and 100% 1RM (one repetition maximum) load. Explanation of followings symbols in the text.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>70% 1RM</th>
<th>100% 1RM</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB</td>
<td>15.9</td>
<td>30.5</td>
</tr>
<tr>
<td>GMed</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>RF</td>
<td>13.8</td>
<td>17.5</td>
</tr>
<tr>
<td>BF</td>
<td>13.2</td>
<td>14.2</td>
</tr>
<tr>
<td>GMax</td>
<td>96.5</td>
<td>77.1</td>
</tr>
<tr>
<td>ES</td>
<td>32.3</td>
<td>40.8</td>
</tr>
</tbody>
</table>
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**Table 2.** Mean of modules of amplitude differences – MMAD [% MVC] for the pairs of homologous muscles of lower extremities of R.N. subject. Attempts of squat movement were performed with a 70 and 100% 1RM load. Explanation of followings symbols in the text.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>70% 1RM</th>
<th>100% 1RM</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB</td>
<td>8.1</td>
<td>10.3</td>
</tr>
<tr>
<td>GMed</td>
<td>9.2</td>
<td>11.2</td>
</tr>
<tr>
<td>RF</td>
<td>11.2</td>
<td>9.5</td>
</tr>
<tr>
<td>BF</td>
<td>11.5</td>
<td>10.2</td>
</tr>
<tr>
<td>GMax</td>
<td>19.0</td>
<td>28.0</td>
</tr>
<tr>
<td>ES</td>
<td>16.1</td>
<td>30.0</td>
</tr>
</tbody>
</table>

cont. **Figure 1.** – EMG profiles normalized according to amplitude and time [% MVC] for three successive pairs of homologous lower limb muscles (BF – biceps femoris, GMax – gluteus maximus, ES – erector spinae) of subject A.M.. Attempts at squat movement (in the descent and ascent phases) were performed with the following loads: A) 70% 1RM and B) 100% 1RM.
Figure 2. EMG profiles normalized according to amplitude and time [% MVC] for three pairs of homologous lower limb muscles (TB – tibialis anterior, GMed – gastrocnemius medialis, RF – rectus femoris) of subject R.N.. Attempts at squat movement (in the descent and ascent phases) were performed with the following loads: A) 70% 1RM and B) 100% 1RM.

Table 3. Mean of modules of amplitude differences [% MVC] for the pairs of homologous muscles in descent and ascent phases (MMAD_{des} and MMAD_{asc}, respectively) of squat movement of A.M. subject. Attempts of the squat were performed with a 70 and 100% 1RM load. Explanation of followings symbols in the text.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>70% 1RM</th>
<th>100% 1RM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Descent phase MMAD_{des}</td>
<td>Ascent phase MMAD_{asc}</td>
</tr>
<tr>
<td>TA</td>
<td>23.5</td>
<td>8.5</td>
</tr>
<tr>
<td>GMed</td>
<td>5.2</td>
<td>1.9</td>
</tr>
<tr>
<td>RF</td>
<td>10.8</td>
<td>16.8</td>
</tr>
<tr>
<td>BF</td>
<td>4.5</td>
<td>21.8</td>
</tr>
<tr>
<td>GMaks</td>
<td>38.1</td>
<td>153.7</td>
</tr>
<tr>
<td>ES</td>
<td>21.1</td>
<td>43.3</td>
</tr>
</tbody>
</table>
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**Table 4.** Mean of modules of amplitude differences [% MVC] for the pairs of homologous muscles in descent and ascent phases (MMAD_{des} and MMAD_{asc}, respectively) of squat movement of R.N. subject. Attempts of the squat were performed with a 70 and 100% 1RM load. Explanation of followings symbols in the text.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>70% 1RM</th>
<th>100% 1RM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Descent phase</td>
<td>Ascent phase</td>
</tr>
<tr>
<td></td>
<td>MMAD_{des}</td>
<td>MMAD_{asc}</td>
</tr>
<tr>
<td>TB</td>
<td>9.5</td>
<td>6.5</td>
</tr>
<tr>
<td>GMed</td>
<td>8.7</td>
<td>9.7</td>
</tr>
<tr>
<td>RF</td>
<td>10.4</td>
<td>12.1</td>
</tr>
<tr>
<td>BF</td>
<td>11.6</td>
<td>11.8</td>
</tr>
<tr>
<td>GMax</td>
<td>20.0</td>
<td>18.0</td>
</tr>
<tr>
<td>ES</td>
<td>15.4</td>
<td>16.9</td>
</tr>
</tbody>
</table>
Data from Tab. 1 indicate that subject A.M., in the 100% 1RM test, is generally characterized by higher asymmetry (increase in the MMAD value) than in the squat with a 70% 1RM load. In the case of the *tibialis anterior* muscle, the MMAD value was almost twice as high; however, with respect to the *gluteus maximus* muscle, it was smaller. For the other four muscles, the MMAD value was also higher during the squat with a 100% 1RM load, although not as much as for the *tibialis anterior* muscle (Tab. 1). The second stage of the squat was usually accompanied by a larger MMAD increase for individual muscles (Tab. 3, MMAD_g), with the exception of the *gastrocnemius medialis* muscle.

In relation to the second subject (R.N., Tab. 2), the MMAD value for one of the muscles (*erector spinae* – ES) was almost twice as high during the squat, and the second one (*gluteus maximus* – GMax), almost one and a half times higher than obtained in the trial with a moderate load (70% 1RM). There were, however, 2 muscles (*rectus femoris* – RF, *biceps femoris* – BF) for which the MMAD value in the squat with 100% 1RM load was slightly smaller. Nonetheless, it cannot be said that the increase in the accepted measure of symmetry occurred mainly during the ascent phase (Tab. 4), it was rather uniform.

4. Discussion

In the past, profiles (graphs) of lower limb electromyograms showing muscle activity were used to assess gait as a measure of disorders (abnormal) in neuromuscular function [19] and when walking at different rates [4]. However, we were interested in the profiles of muscle activity during a full squat with a barbell on the shoulders and with an increasing load. Amplitude values and the temporal EMG profile were used considering functional symmetry of homologous muscles of the left and right lower limb, i.e. bilateral or two-sided muscles. On the basis of such profiles, some differences can be detected, too subtle, however, for their direct observation.

To determine whether the EMG profile of the specific lower limb muscle is appropriate, it was compared with the profile of the homologous muscle of the other limb. Arsenault et al. [9] quantitatively demonstrated (based on correlation coefficients) the high degree of symmetry in EMG profiles for the population on the example of horizontal gait in a strongly differentiated group of subjects, i.e. for the totalled (global) mean values of all the characteristics (grand ensemble averages [4, 7, 11]) of two homologous muscles (*rectus femoris* and *soleus*). In our case, the second limb was a good foundation for comparison, because it was possible to avoid population variables, and at the same time, to show the impact of load size on symmetry.

With reference to the squat, Robertson et al. [7] presented linear envelope electromyograms as muscle activity profiles. They were normalized for the maximal voluntary contractions of each subject. Recently, similar characteristics were obtained for performing a squat with a barbell by Yavuz and Erdag [8]. The shapes of our RMS EMG [% MVC] characteristics, obtained separately for the left and right lower limbs (Fig. 1 and 2) also show high agreement with these envelopes. This allowed to determine the symmetry degree of the homologous muscle activity.

For this purpose, the normalized characteristics of RMS EMG were compared at points temporally normalized. For individual homologous muscle pairs, the mean of modules of amplitude differences from all points is the measure of symmetry of EMG profiles. Taking the entire squat movement with the 100% 1RM load into account, the subject A.M. is characterized by lower symmetry of the profiles of the homologous muscles tested, compared to the 70% 1RM load, because the MMAD value for these muscle pairs is higher, except for the GMax muscle (Tab. 1). For subject R.N., in the case of two muscles (RF and BF), slightly higher MMAD values were for the 70% 1RM load (Table 2). Although A.M. was characterized by a slightly higher increase in the average difference of amplitudes for individual muscles during the ascent phase (greater asymmetry, Tab. 3, MMAD_g), for R.N., the distribution was already more even and the increase took place during both the 1st and 2nd phases of the squat (Tab. 4).

Nonetheless, there is a relationship between EMG profiles showing muscle activity and motor patterns in people performing various activities of everyday life. On the example of people with trauma of the anterior cruciate ligament, Trulsson et al. [20] showed that during gait, specific, altered movement patterns are associated with deviations in muscle activity between the damage and undamaged side. They stated that “... in order to identify altered motor patterns, reliable, valid and quantitatively observable assessments are needed.” However, we believe that “quantitative observation evaluation” is not enough – measurements need to be performed.

In this study, as has been mentioned several times, a full shoulder barbell squat with moderate and maximal loads was analysed, and the characteristics of the knee joint angle were considered as the motor pattern. Yavuz and Erdag [8] mention the change in hip joint pattern along with an increase in trunk inclination during the performance of squats with a maximum load. However, this has not been verified in our analysis. Nevertheless, large differences were found in the compared temporal characteristics of the angle in the knee joint of the two subjects (A.M. and R.N.) with a 100% 1RM load, which can be seen in Figure 3 (during the ascent phase).
This is also confirmed by the recordings conducted using an additional digital camera, in which the knee joint and the hip girdle rotations (once in one direction and then in the opposite) occur during A.M.’s ascent phase. The image of these movements is, among others, the mentioned, irregular angle change (decreases and increases) in the knee joint. The loss of movement fluidity [17] visible in the case of subject A.M. may be associated with slightly higher asymmetry of activity (i.e. slightly higher MMAD_{des} values compared to MMAD_{asc}), the main muscles propelling and stabilizing the knees and the hip girdle (RF, BF, GMax and ES). However, similar differences also occurred in A.M. during the trial with the 70% 1RM load.

According to Arendt-Nielsen et al. [22], clinical and experimental results indicate that during gait, this motor activity is modulated by musculoskeletal pain, probably as a reflex. Perhaps in the case of squatting with a barbell on the shoulders, such a factor modulating the pattern of this movement is the very high load during the 100% 1RM test (high intensity of this exercise). Although the technique of movement (sports) is recommended to remain independent of the intensity of the exercise [23], from the observation of many coaches, it follows that if the load reaches the limits of athletes’ ability, they can change the movement pattern of the performed exercise. And this is probably the case of the squat examined for A.M.

Figure 3. Temporally normalized [%] knee joint angle-time curves of subjects A.M. (-----) and R.N. (-----). Attempts at squat movement (in descent and ascent phases) were performed with the following loads: A) 70% 1RM and B) 100% 1RM.

5. Conclusions

The increase in the size of the load during the barbell squat caused in an increase in the asymmetry of the selected homologous muscles of the lower limbs. Its expression is the higher MMAD values in both presented cases (subjects A.M and R.N.). However, the data for the first subject deserve particular attention, in which the greater asymmetry occurred mainly during the ascent phase (higher MMAD_{des} values in comparison to MMAD_{asc}). Subject R.N. was characterized by a more uniform MMAD distribution in both phases.

The relationship of EMG profiles with motor patterns may be indicated by the characteristics of knee joint of both subjects during the ascent phase of the squat with a 100% 1RM load (Fig. 3). A.M. rotated his knees and hip girdle several times while ascending with the barbell (once in one and once in the other direction), which resulted in less smooth movement (uneven change of angle in the knee joint). Perhaps it is a consequence of greater asymmetry in the key fragments of EMG profiles of the main knee and hip girdle muscles involved in squats performed with a maximal load.

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