Neuromuscular efficiency of the rectus abdominis differs with gender and sport practice.

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Neuromuscular Efficiency of the Rectus Abdominis Differs with Gender and Sport Practise

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[†]In memory of Isabelle Mora, who died suddenly in September 2007

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Running head: EMG-TORQUE RELATIONSHIP

ABSTRACT

The purpose of this investigation was to distinguish the abilities of the rectus abdominis (RA) muscle according to gender and sport training by means of neuromuscular parameters extracted from electromyography (EMG)-torque relationships. Thirty-eight healthy students, divided into 4 groups (i.e., 8 male runners, 10 female gymnasts, 12 male controls, and 8 female controls) were asked to perform 6 seconds of isometric trunk flexions at 20%, 25%, 75%, and 100% of their maximal voluntary contraction. Flexion torque and surface EMG of the RA muscle were recorded simultaneously to construct a EMG-torque relationship. Under maximal and submaximal conditions, an index of neuromuscular efficiency (NME) was determined to characterize the capacity of the RA muscle to develop a torque. At each level of contraction, the area of data scattering (ADS), reflecting torque and EMG fluctuations, was computed to express the capacity to maintain a constant target torque. Flexion torque, NME, and ADS values differed significantly between genders, but when data were related to anthropometric characteristics, no difference was observed. Although runners were not distinguished from male controls, gymnasts had higher flexion torque, higher NME, and lower ADS values than female controls had. These differences should reflect neural and muscular adaptations linked to the specificity of gymnastic training. These findings revealed different functional abilities of the RA muscle, according to gender and sport practices. The indices of neuromuscular capacities used in this study could constitute complementary tools to athletic trainers and professionals in sports medicine for evaluating and following, during sport-specific training programs, the abdominal muscle performance implied in force transfers with a lower cost and lower risks of back pain.

KEY WORDS Trunk flexion, isometric contraction, electromyography, electromyography-torque relationship

INTRODUCTION

Performing complex and repeated motor skills, such as those performed by both athletic and active populations, can greatly increase the risk of musculoskeletal injuries. Consequently, strengthening exercises are widely used by athletic trainers and physical therapists to increase stability at joint the level and prevent excessive loads. From this perspective, the assessment of muscle strength represents one of the most common measurements made in exercise physiology laboratories to quantify and improve muscular function. Despite its apparent simplicity of measure, the torque developed at a joint is heavily dependent on psychological factors (e.g., motivation) and on the functional state of the neuromuscular system (e.g., contractile properties and the capacity of subjects to activate all motor units). Furthermore, with patients suffering from conditions such as back disorders, for which osteoligamentous degeneration and muscle dysfunction are often diagnosed, the measure of muscle strength may be limited by pain (31). Thus, the ability for a subject to produce a force and movement cannot be limited to a simple measure of torque obtained by cable tension or strain gauge methods.

The assessment of the functional state of a muscular group by the measure of an index of neuromuscular efficiency (NME) could constitute a relevant alternative. It expresses the ability to develop strength with lower a cost and lower risks of injuries. Since the work of Lippold (24), the NME has been frequently used to assess the functional state of different muscular groups by the establishment of EMG-torque relationships under isometric contractions. These relationships illustrate the increase of muscle activation when the voluntary torque developed by the subject is increased. Defined by the inverse of the slope of the EMG-torque relationship (7,27,28), the NME change can be related to gender (20,38) pathology (23), or training (27,33), reflecting neural or muscular adaptations. When a subject produces a sustained isometric contraction, myoelectrical activities and torque measured in the periphery are not perfectly constant, but rather fluctuate around mean values (9). The magnitude of these fluctuations in motor output has been referred to as the ability for a subject to maintain precise target torque (32). It has been shown that these fluctuations are more pronounced in elders (9) and that they can be reduced through practice and strength training (21). Thus, these parameters extracted from EMG-torque relationships could be valuable tools for the assessment of muscle efficiency.

Oddly enough, the functional state of abdominal muscles has always been poorly documented. Nevertheless, the weakness of abdominal muscles (i.e., muscle strength, endurance, and pattern recruitment) is commonly mentioned as a major indicator of potential low back pain (37). In the field of sport activities, motor performance is determined not only by the capacity of the neuromuscular system to achieve the desired movement but also by the quality of postural support given to intentional movement. For a successful skill execution at a lower cost with reduced risk of back injuries, a dynamic core stabilization training (i.e., improving strength, endurance and neuromuscular control of the trunk musculature) represents a key component of the training programs for athletes (3). Furthermore, this suggests that different capacities of abdominal muscles may be expected between athletes and sedentary people or between men and women insofar as the neuromuscular behavior of trunk muscles related to spine stability has been reported to be gender-dependent (14,15,25).

Accordingly, the purpose of this study was to distinguish abdominal muscle abilities according to gender and sport training by quantifying NME and fluctuations of EMG and torque data from EMG-torque relationships established in trunk flexion. Two types of sports (i.e., gymnastics and middle-distance running) were chosen for which abdominal musculature is involved differently and between which different abdominal muscle abilities could be expected. While in middle-distance running, the abdominal muscles are implied at a moderate level in spine stabilization and in breathing assistance, they are more strongly required in gymnastics for the trunk sheathing necessary to the execution of complex figures. This pioneer investigation may permit not only the determination of normal values but also the proposition of a straightforward method to evaluate and follow the performance and improvement of abdominal abilities. Such data may interest athletic trainers and professionals in sports medicine to develop the most effective training methods for athletes in relationship to their physiological abilities and their sport specificity, notably by optimizing the force transfers between the lower and upper limbs.

METHODS

Experimental Approach to the Problem

Flexion torque produced by isometric contractions of the abdominal muscles was measured with a Cybex Norm isokinetic dynamometer (Lumex, Inc., Palatine, IL). Subjects were seated comfortably with their arms hanging alongside their trunk (Figure 1). In this sitting position, the contribution of the psoas iliac muscle to trunk flexion torque was limited and the subjects could follow the instructions displayed on the computer screen more easily. A back support was adjusted to maintain the hip at 90° of flexion. The legs were placed at each side of the chair so that their contribution to the required effort could be avoided. To block movements of trunk flexion and ensure isometric contractions of the abdominal muscles, a rigid rod was placed beneath the line joining the shoulders and connected to the dynamometer axis for flexion torque measurements. A pad was attached to the rod to prevent any discomfort when the subjects exerted trunk flexions. The subjects were positioned so that L5-S1 was aligned with the axis of rotation of the dynamometer. The torque output was displayed in real time on an oscilloscope for feedback.

Acting as the prime mover in trunk flexion, the rectus abdominis (RA) muscle was chosen to represent the trunk flexor muscle group. Electromyographic (EMG) bipolar recording of the RA muscle activity was made on the right side of the body to avoid interferences from cardiac activity by using Ag-AgCl surface electrodes 8 mm in diameter (Beckman Coulter, Inc., Fullerton, Calif.). Before their placement, the skin at the electrode sites was prepared to achieve an interelectrode impedance of less than 5 kΩ. The electrodes (center-to-center spacing, 20 mm) were placed approximately 2 cm lateral to the midline and 1 cm superior to the umbilicus (30), parallel to the muscle fibers. The reference electrode was placed on the sternum.

The EMG signal was differentially amplified (input impedance, 11.6 MΩ, common mode rejection ratio, 100 dB at 60 Hz; Gould 6600, Cleveland, Ohio) with a gain set between 1000 and 5000 and filtered by using a bandwidth of 10 to 1000 Hz. The EMG and torque signals were simultaneously sampled at 1000 Hz by using a 12-bit analogue-to-digital converter (National Instrument Daq Card-AI-16E-4). The data were collected on a laptop computer interfaced with DataSet Pro software (SETRI, Mantes-la-Jolie, France) and then stored for offline processing.

Subjects

A total of 38 healthy students volunteered to participate in this noninvasive study. None of them had a history of neuromuscular disorders. The study was conducted in accordance with the guidelines for the use of human subjects as stipulated by the 1964 Declaration of Helsinki. Informed consent was obtained for all subjects after the risks and benefits associated with the study had been fully explained and understood. Two control groups comprised 20 recreational sport practitioners, 12 men (CM) and 8 women (CW), recruited from the department of Sport Sciences at the University of Picardie in Amiens, France. All moderately took part (<5 hours per week) in various sporting activities (e.g., tennis, football, basketball, and swimming), and none were members of a competitive team. In addition, none had previously participated in systematic strength training programs of the abdominal muscles. They were respectively compared to a group of 8 men specialized in middle-distance running (RM) and to a group of 10 expert women in gymnastics (GW). These competitive athletes exercised approximately 15 hours per week for 5 to 8 years. They regularly participated in competitions at a regional level or higher. Apart from their training program, none of these athletes had participated in any strength training program involving the abdominal muscles. Subject characteristics are listed in Table 1.

Experimental Procedure

First, all subjects were familiarized with the tests by exerting submaximal isometric efforts of trunk flexion. They were asked to keep their legs and arms relaxed, without hand gripping of supports on the body or on the ergometric device. These preliminary trials were also used for the warm-up. After this phase of learning and warming-up, 3 maximal voluntary contractions (MVCs) in trunk flexion were required in 6 seconds, with 45 seconds of rest after each contraction to prevent fatigue. Visual feedback and verbal encouragements were given to ensure that the subject produced a maximal effort of trunk flexion. The highest torque value generated in these maximal isometric contractions was retained as the maximal torque and used to set target levels for submaximal isometric contractions. After the MVC session, the subject rested for 4 minutes. Three sets of submaximal contractions, 6 seconds in duration, were then performed randomly at 25%, 50%, and 75% of the MVC, with 4 minutes of rest after each set. A set of submaximal voluntary contractions consisted of 3 trials spaced by 45 seconds of rest. To maintain steady submaximal contractions, the subject was instructed to overlap the output torque signal and the target trace corresponding to the required torque level. The torque signal and the target trace were displayed on the oscilloscope placed approximately 80 cm in front of the subject's eye level. From the 3 trials at each target torque, the one with the most constant torque (i.e., with the weakest value of *SD* of torque) was chosen for subsequent analysis.

Data Processing

The offline processing of EMG and torque signals was performed for each contraction by using a microcomputer application written with Matlab 6.5 (The Mathworks Inc., Natick, MA). In 4 seconds of steady phase of contraction (i.e., minimal fluctuations of torque), the RA muscle EMG was first rectified, and then, EMG and torque signals were treated by using a sliding average method to quantify, as proposed by Pérot et al. (32), the scattering of data during a steady contraction. This method consisted of measuring the mean amplitudes in windows of 300 ms in duration, with a sliding step of 20 ms to get 185 values for each signal. For each subject, EMG data measured under maximal and submaximal efforts were expressed as a percentage of the maximal value obtained among the 185 EMG values measured under MVC (i.e., normalized EMG data). The 185 EMG and torque values at each level of contraction were used to construct the EMG-torque relationship, with data represented as a cloud of points (Figure 2). Linear and curvilinear regression analyses, using the least squares method, were carried out to characterize the shape of the EMG-torque relationships. The best fitting corresponded to the higher coefficient of determination (r^2), calculated from the correlation coefficient (r) of Bravais-Pearson. The better regression was obtained with the exponential function ($r^2 = 0.88 \pm 0.05$; $n = 38$). At the MVC, a first index of neuromuscular efficiency (NMEmax) was defined by the ratio between the maximal value of torque and the mean value of the 185 normalized EMG values. Under submaximal conditions, the exponential regression curve of the EMG-torque relationship was linearized by a logarithmic transformation of scales and the inverse of the slope gave a second neuromuscular index (NMEsubmax). To express the difficulty for the subjects to maintain a target isometric torque and the corresponding level of muscle activation (32), the area of data scattering (ADS) was computed at each level of contraction by using the Delaunay triangulation method (1) and normalized with respect to MVC torque. To establish the reliability of torque and EMG measures, the intraclass correlation coefficient (ICC) was estimated by using a 1-way analysis of variance table. Torque and EMG measures showed high ICC values (range, 0.84-1 and 0.63-0.99, respectively) in the test-retest design, which indicate a high reliability of the measures.

Statistical Analyses

Values are reported as means ± *SD*. Correlation analyses were used to determine relationships between MVC torque values and anthropometric characteristics of the subjects. Analysis of variance (ANOVA) or the Kruskall-Wallis test, when the normality test failed, was used to compare normalized EMG and ADS values according to the level of contraction. When the analysis indicated the presence of a significant difference, the means were compared by the Student-Newman-Keuls test. To compare anthropometric variables, MVC torques, normalized EMG, NME, and ADS values according to gender and sport practice, the Student *t*-test or the Mann-Whitney test, when the normality test failed, was performed. The α level was set at 0.05 to identify statistical significance. All analyses were conducted with Statview 5.0 (SAS Institute Inc., Cary, NC).

RESULTS

Maximal Trunk Flexion Torque

At the MVC, the mean torque value was 161.9 ± 55.1 N·m for CM and 123.9 ± 22.2 N·m for CW. However, the difference between these 2 groups was not significant ($p = 0.07$). Because the weight and height of the CM were higher than those of the CW (Table 1), the differences between the 2 groups cancelled when MVC torques were related to these anthropometric variables. As the anthropometric data did not change between the 2 groups of men (Table 1), no difference was found in MVC torques between the RM (155 ± 43.3 N·m) and CM. Although the weight and body mass index (BMI) of the gymnasts were lower than those of the CW (Table 1), the MVC torque developed by the GW (148.3 ± 31.6 N·m) tended to be higher than that developed by the CW ($p = 0.08$). This trend became significant when MVC torques were related to the weight, height, or BMI of these subjects ($p < 0.05$). For example, the mean amplitude of MVC torque-to-weight ratio was 2 ± 0.3 for the CW and 2.7 ± 0.5 for the GW.

Neuromuscular Efficiency

The NME indices of the 4 groups of subjects calculated under maximal and submaximal conditions are shown in Table 2. The CM had higher NMEmax and NMEsubmax values than the CW had ($p < 0.05$). No significant differences were observed for NME indices between the RM and CM, while the GW had higher NMEmax and NMEsubmax values than the CW had ($p < 0.05$).

Torque and Electromyographic Fluctuations

As illustrated in Figure 2, the increase in the contraction level was obviously associated with an exponential increase in levels of the RA muscle. For all groups of subjects, analysis of the scattering of EMG and torque data indicated significant increases in ADS values with the contraction level (Figure 3). At the MVC, the CW had lower ADS values than the CM had ($p = 0.02$). The ADS values of gymnasts were lower than those of the CW at all levels of contraction, but the differences were only significant at the MVC ($p = 0.03$).

DISCUSSION

The ability of the RA muscle to develop a torque level was explored in relation to gender and sport practice during maximal and submaximal isometric trunk flexion contractions. It was hypothesized that the indices of NME and the fluctuations of torque and EMG (i.e., parameters extracted from the EMG-torque relationship) could be relevant indicators of the functional state of the RA muscle according, to the different needs of trunk sheathing. Basic differences in muscle strength can be easily measured, but they do not give a whole representation of neuromuscular abilities. The abdominal muscle strength that must be developed to promote a sport performance is not necessarily the maximal strength that these muscles can generate. The muscle activation must take into account muscle capacities, morphological characteristics (e.g., lever arms of muscles), and antagonist coactivations, which are known to depend on learning and the intensity of motor tasks. Muscle capacities and morphological characteristics are well illustrated in the maximal condition of strength development, but the abilities of the nervous system to activate adequately the implied muscles are better illustrated in submaximal contractions (i.e., patterns of agonist-antagonist muscle activations, which influence the cost of the task and the articular constraints).

As found by Wessel et al. (40) in a similar task of trunk flexion, the maximal torque of trunk flexion produced by men is higher than that produced by women. Under maximal contraction, no difference in absolute or normalized EMG data was found. The EMG data could be influenced by the subcutaneous fat thickness over the RA muscle (11). However, no difference was found in this study in the subcutaneous fat thickness values between men and women. Thus, the gender-related differences in abdominal strength and NMEmax can be imputed to anthropometric characteristics. Indeed, when maximal torque values were related to weight or height, the differences between men and women disappeared. In the same way, when NMEmax indices were calculated with MVC torque-to-weight ratio, gender-related differences were also cancelled. In fact, a major predicator of muscular abilities to generate force is the physiological crosssectional area (4,12,34), predicted for trunk muscles by combinations of body weight and height (26,35). The shorter length of the lever arm of the RA muscles in women than in men (18,35) represents another peripheral factor that could partly contribute to differences in MVC torque values between men and women. Furthermore, due to their greater difficulty to maintain trunk stability (6,13), women have a higher coactivation of antagonist muscles (14,15,25), which could entail a higher opposite extensor torque. Nevertheless, this extensor torque should reduce the net torque measured at the trunk level with an equal amount in women and men because the lengths of lever arms of the extensor trunk muscles are also shorter in women than in men (18,35).

For the RA muscle, the contribution of peripheral factors to the gender-related differences in the ability to produce maximal torque has been confirmed by data analysis of torque and EMG fluctuations. Indeed, ADS values were found to be lower in women due to weaker *SD*s values of the torque data (12.9 ± 6.4 for the CM versus 6.8 ± 2.1 for the CW at the MVC, $p = 0.007$), without gender-related differences in the *SD*s values of the EMG data. Therefore, the fluctuations of torque imputed to the variability of the motor unit recruitment (9,22,36) are attenuated in women because of the shorter lever arms of the trunk muscles.

Under submaximal contractions, the lower values of NMEsubmax measured for the women show a relative overactivation of the RA muscle. Thus, for a similar task or to generate a similar account of torque, women must develop greater RA muscle activity, which could lead to a higher risk of back injuries. Thus, the gender-related differences must be taken into account to design an adapted training program of this muscle.

Biomechanical and physiological adaptations of skeletal muscles induced by sport training have been widely studied and have been made the subject of several reviews (8,10,17). Because the abdominal muscles play an important role in spine stability and force transfer between the lower and upper limbs, their reinforcement by sport practice has become a key component of training programs and represent a potential protective factor of musculoskeletal injuries. In this context, the authors have suggested that sport training should induce peripheral or central adaptations of the abdominal muscles, which could be evidenced by the analysis of the RA muscle EMG-torque relationships. This study considered gymnasts and middle-distance runners, whom the abdominal muscles are involved differently. Apart from their common participation in spine stability, the abdominal muscles are more recognized for their respiratory function in middle-distance running, whereas in gymnastics, the execution of figures involves the abdominal muscles as prime movers in both isometric and anisometric (i.e., concentric and eccentric) conditions.

No significant difference was found in this study between the CM and RM, regardless of the parameter considered. Therefore, the respiratory solicitation of the RA muscle during running does not seem consistent enough to improve the efficiency of this muscle. However, significant differences were found between the GW and CW. When performing MVCs, the GW produced higher maximal trunk flexion torques than the CW despite their weaker body mass, and they exhibited higher NMEmax. It brought higher maximal torque to body weight ratios and higher NMEmax for the GW. Such improvements by strength training have already been reported for other muscle groups (5,29) and explained in terms of muscular and neural adaptations. Because the GW had higher NMEmax without difference in both EMG data and subcutaneous fat thickness values, it was reasonable to attribute these modifications to muscular adaptations, notably to an improvement of the contractile properties of the RA muscle. Under submaximal contractions, the higher NME indices found for the GW could reflect these muscular adaptations, but also central adaptations, such as a better coordination between muscles implied in the task. This latter hypothesis involves better patterns of coactivation within synergistic muscles (i.e., prime mover and stabilizer), and lower agonist-antagonist cocontractions of trunk muscles, as described for different muscle groups after muscle training (16,33).

The contribution of neural adaptations for the RA muscle linked to gymnastic training is also demonstrated by the ability to maintain steady trunk flexion efforts. Indeed, lower ADS values during low and high levels of contraction were obtained for the GW compared to the CW, mainly due to the lower *SD*s of the EMG data (18.6 ± 5.1 for CW versus 15.1 ± 1.5 for GW at the MVC, $p = 0.02$). Therefore, as reported earlier, through training protocols conducted in old adults (19,21) and subjects with disease (2), the results of the current study are consistent with the idea that the ability of the GW to control their flexion torque output was due to an improved capacity of the nervous system to activate and coordinate the concerned muscles. Because the NME and ADS parameters have permitted the distinguishing of subjects for whom the RA muscles abilities related to sport practice were supposedly different, the relevance of these parameters extracted from EMG-torque relationships has been demonstrated.

PRACTICAL APPLICATIONS

The establishment of EMG-torque relationships under isometric contractions proved to be a practical tool in the assessment of motor performance. Applied to the RA muscle, the neuromuscular parameters extracted from these relationships (e.g. index of NME and ADS) permitted the underscoring of gender differences explained by peripheral factors (i.e., individual characteristics) and sport-specific differences justified by muscular and neural adaptations. These adaptations can be linked to an improved performance in load transfers with a lower cost and reduced risks of back injuries. This investigation of NME and ADS parameters in the current study provides a baseline for comparison in future analyses of different athletic populations and different training methods. In addition, the data could turn out useful for trainers or physicians to provide athletes with regular followup and to develop effective training programs in accordance with their sport and physiological abilities (i.e., age, gender, expertise level and training history).

At the trunk level, it was shown that neuromuscular behavior depended on the muscle solicited and the orientation of trunk movement (39). Thus, additional experiments involving other trunk muscles and carried out at various joint angles would provide new insights into the functional state of these muscles. Their implementations in a clinical setting (e.g., with patients with lower back disorders for which musculoskeletal disorders, neuromuscular inefficiencies, and poor physical conditioning predispose to the development of chronic disability) could be interesting and useful to create a better understanding of the involved mechanisms of spine stabilization in various occupational tasks.

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TABLE 1. Subjects characteristics.

	Women Gymnast (GW) (n = 10)	Men Runners (RM) (n = 8)	Women Controls (CW) (n = 8)	Men Controls (CM) (n = 12)
Age (y)	21.3 ± 2	22 ± 4.4	21.8 ± 2	20.8 ± 2.4
Height (cm)	1.6 ± 0.1	1.8 ± 0.04	1.7 ± 0.04	1.8 ± 0.1*
Weight (kg)	55.4 ± 6†	70.6 ± 6	62.8 ± 7.3	75.4 ± 11.9‡
BMI (kg.m^2)	20.8 ± 1.4	21.8 ± 1.6	22.5 ± 2.1	23 ± 2.4
Subcutaneous fat thickness (mm)	12.5 ± 2.4	12 ± 3.1	15.2 ± 3.3	15 ± 5.2

Data are presented as mean ± *SD*. The thickness of the abdominal fat was measured at the electrode sites (2 cm lateral to the midline and 1 cm superior to the umbilicus) by using a caliper.

*Significant difference between men control and women control groups at $p < 0.01$.
†Significant difference between gymnasts and women control groups at $p < 0.05$.
‡Significant difference between men control and women control groups at $p < 0.05$.

TABLE 2. Index of neuromuscular efficiency.

	Women Gymnast (GW)(n = 10)	Men Runners (RM)(n = 8)	Women Controls (CW)(n = 8)	Men Controls (CM)(n = 12)
NMEmax	2.7 ± 0.3*	3 ± 1.2	2.2 ± 0.4	3.7 ± 1.6†
NMEsubmax	22.4 ± 6.6*	20.1 ± 9.2	15.6 ± 3.4	22.8 ± 5.6†

Data are presented as mean ± *SD*. For each subject, the NMEmax was calculated as the ratio between the MVC torque and the mean of normalized EMG values. The NMEsubmax was determined from the inverse of the slope of EMG-torque relationship linearized by the logarithmic transformation of scales.

*Significant difference between gymnasts and women control groups at $p < 0.05$.

†Significant difference between men control and women control groups at $p < 0.05$.

NMEmax = maximal neuromuscular efficiency; NMEsubmax = submaximal neuromuscular efficiency; MVC = maximal voluntary contraction; EMG = electromyography.

FIGURE 1. Subject positioning for isometric testing of the rectus abdominis muscle.

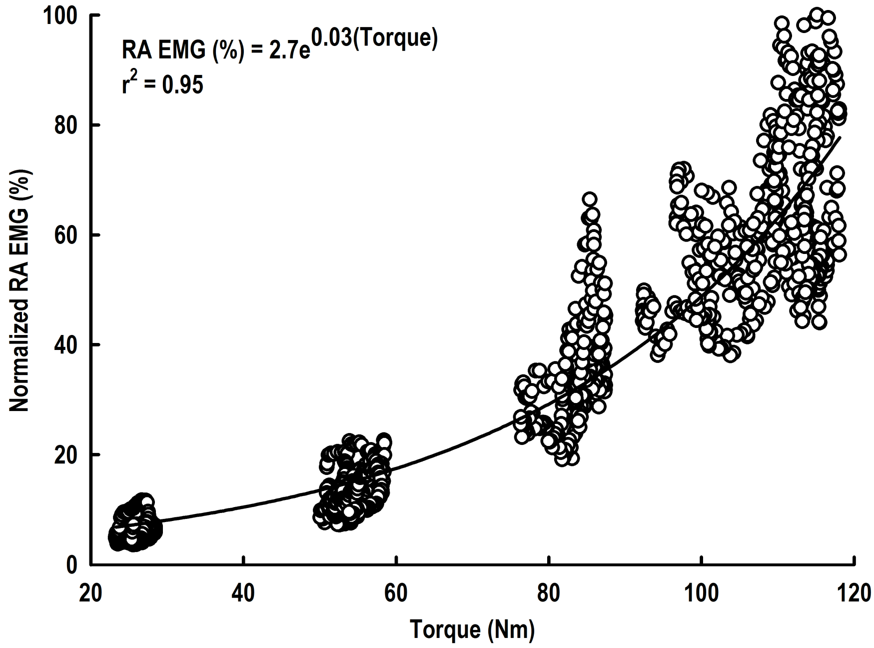

FIGURE 2. Example of electromyography-torque relationship established for the rectus abdominis muscle during isometric efforts of trunk flexion at 25%, 50%, 75% and 100% of the maximal voluntary contraction (MVC). Electromyographic data were calculated by using a sliding average method and expressed in percentage of the highest value reached in the MVC.

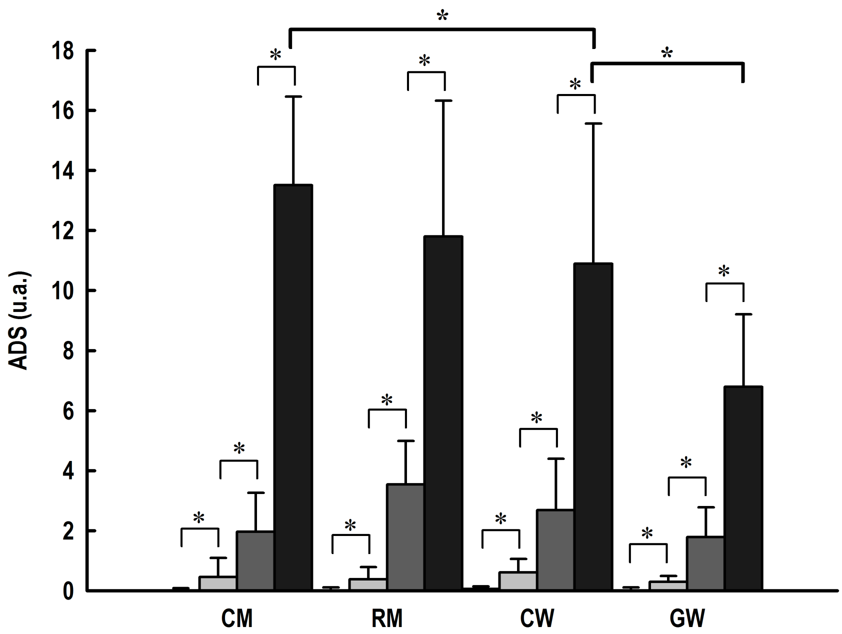

FIGURE 3. Areas of data scattering (ADS) calculated for the rectus abdominis muscle in men controls (CM), men runners (RM), women controls (CW), and women gymnasts (GW) during isometric trunk flexions at 25%, 50%, 75% and 100% maximal voluntary contraction (MVC). For each level of contraction, the ADS was computed by using the Delaunay triangulation method and normalized to the MVC torque. Means plus one *SD* are represented. *Significant difference at $p < 0.05$.