

Electromyography and peak torque analysis in football players as indicators of fatigue during isokinetic concentric contractions of the rectus femoris EMG and torque analysis for fatigue in football players

GONÇALO AGOSTINHO¹, MICHELE ROSA², MAURÍCIO ROSA³

¹ Faculty of Medicine of the University of Lisbon, Lisbon, PORTUGAL;

^{2,3} Cardiovascular Centre of the University of Lisbon, Lisbon, PORTUGAL;

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Abstract

Background: This study investigates the potential of electromyographic (EMG) analysis using the Bitalino device in combination with peak torque measurement to evaluate muscle fatigue during isokinetic concentric contractions of the rectus femoris muscle in football players. By analysing muscle activity in real-time, EMG provides valuable insights into the physiological responses of muscles under exertion, paving the way for targeted interventions to improve athletic performance. This approach offers a non-invasive and efficient method to monitor fatigue levels, enabling the optimization of training regimens, injury prevention strategies, and overall performance enhancement. The integration of EMG analysis with real-time data from peak torque measurements holds significant promise for refining personalized training protocols tailored to the unique needs of each athlete.

Methods: Five male football players from the U18 and U19 teams of Belenenses participated. Athletes performed six maximal concentric dynamic contractions of both knee extension and flexion on a Biodex System 4 isokinetic dynamometer. EMG signals were captured through surface electrodes, and peak torque was recorded. EMG data underwent processing to compute root mean square (RMS) and mean frequency (MNF) during contractions. **Results:** The analysis revealed a correlation between peak torque and EMG variables. Specifically, in 40% of the subjects, peak torque decreased while RMS increased, and MNF decreased as fatigue set in. This trend was particularly pronounced in the dominant leg for most athletes. Additionally, the dominant leg displayed lower EMG (mV) variability, potentially reflecting greater energy efficiency and muscle coordination compared to the non-dominant leg. **Conclusion:** The identified 40% correlation represents an important preliminary finding, suggesting a relationship between peak torque and EMG variables that may serve as indicators of fatigue during dynamic contractions in a subset of this sample. The observed energy efficiency in the dominant leg underlines the potential impact of muscle coordination and usage frequency on performance. However, the small sample size limits the generalizability of these findings. Expanding future research to include a larger cohort and a broader range of athletic activities is essential for validating these results and refining the application of EMG and peak torque analysis in sports performance optimization.

Keywords: Surface Electromyography, Neuromuscular Efficiency, Fatigue Assessment Metrics, Concentric Muscle Dynamics, Real-time Muscle Monitoring, Athletic Performance, Isokinetic Strength Evaluation, Sports Biomechanics.

Introduction

The field of sports science has undergone a profound evolution in response to the substantial investment that has been made in it. As the demand for evidence-based training methodologies grows, the integration of advanced tools like electromyography (EMG) has become increasingly critical. EMG offers a precise method of analyzing muscle activity, contributing to a comprehensive clinical assessment. In addition to its utility in the clinical setting for non-athletic patients, in the field of sports physical activity, the use of EMG can be beneficial in enhancing the effectiveness of a given movement and in evaluating fatigue, co-activation and biofeedback. Consequently, during practice, for instance, by analysing the parameters of the EMG signal, it is possible to enhance muscle activation, diminish fatigue and assess potential injury risks (Fernández-Lázaro et al., 2020; Massó et al., 2010).

The need for this research arises from the limitations in current applications of EMG in dynamic sports environments. Despite its potential, most studies rely on static contractions, which fail to replicate the complexity of athletic movements. This gap in knowledge has left a critical question unanswered: how reliable are EMG indicators of fatigue during dynamic sports activities? Addressing this is crucial for improving athlete performance and developing injury prevention strategies.

Fatigue is a topic that is frequently discussed in the field of sports science. Vøllestad defined fatigue as follows: "Any exercise-induced reduction in the capacity to generate force or power output" (Vøllestad, 1997). Several indicators can be employed to infer the fatigue of a particular athlete. In the field of surface EMG, the

most utilised indicators are Root Mean Square (RMS) and Mean Frequency (MNF). These provide respectively, information on the amplitude and frequency of the EMG signal during physical activity. In the case of sustained static contractions, it is typical for both variables to undergo a shift: the RMS tends to increase and the frequency to decrease (spectral shift), which is characteristic of muscle fatigue when an athlete is under high strain (Duchêne & Goubel, 1990).

Most of the EMG evidence comes from studies based on static contractions with no change in posture, which allows many confounding variables to be eliminated. Although static contractions can give us a general idea of an athlete's biometric data, they don't represent the muscular reality during sports activities and extrapolating the results obtained to a competitive environment is unreliable. For this reason, assessing dynamic contractions would be ideal, unfortunately EMG reliability in this is relatively low (Farina, 2006). Nevertheless, Larsson concluded that peak torque, as well as the mean frequency and the root mean square of the rectus femoris and vastus medialis, are reliable indicators of fatigue obtained from an isokinetic endurance test of the knee extensors (Larsson et al., 2003).

The rectus femoris is very complex and has several intrinsic factors that contribute to its high proximal injury rate, as it is the only muscle that covers 2 joints of the quadriceps group and is responsible for the flexion of the thigh and extension of the knee (Hasselmann et al., 1995). Also it possesses majorly type 2 fibres in its constitution, which are characteristically fast and explosive fibres, and therefore has a higher risk of developing injury mechanisms (Kary, 2010). The movements most associated with damage to this muscle are kicking, especially when repeated, as this movement involves an explosive eccentric contraction of the rectus femoris, resulting in an uneven load between the two proximal heads and muscle activation with a low degree of synchrony (Hasselmann et al., 1995; Kary, 2010; Mendiguchia et al., 2013). The high injury rate and functional importance of the rectus femoris make it an ideal focus for EMG-based fatigue research, particularly in dynamic sports environments.

There are also clear advantages to analysing the rectus femoris over other quadriceps muscles from an electromyographic perspective. According to the study conducted by Kollmitzer J. et al. electromyographic data from the rectus femoris was considered more reliable than that from the lateral and medial vastus. They also concluded that EMG fatigue changes were only optimal when the rectus femoris MNF was assessed (Kollmitzer et al., 1999). This study aims to address these gaps by analyzing EMG indicators of fatigue in the rectus femoris during dynamic sports movements. By evaluating the reliability of RMS and MNF in this context, we seek to provide actionable insights for enhancing performance monitoring and injury prevention in athletes. Our approach combines advanced EMG analysis techniques with a focus on dynamic contractions, bridging the gap between laboratory findings and real-world sports applications.

Materials and methods

Materials

Five volunteers (male) football players from Belenenses, a well-known club in Portugal, U18 and U19 took part in this study. The study was approved by the local ethics committee and written informed consent was obtained from all subjects prior to inclusion. No athlete who took part in the study had an active muscle, joint or ligament injury.

Methods

Data collection

The initial stage of the procedure involved the athletes undertaking a 6-minute warm-up on a static bicycle at a low level of exertion, in accordance with the warm-up protocol for isokinetic testing as outlined by the clinic where the tests were carried out. Following this, five disposable razors were utilised, one for each athlete, to shave the thigh hair in the area where the electrodes would be inserted. Afterwards, alcohol was applied and allowed to evaporate before the electrodes were placed in accordance with SENIAM standards. In terms of electrode placement, the 2 bipolar electrodes, with an inter-electrode distance of 20 mm, were positioned on the rectus femoris at 50% of the line joining the anterior superior iliac spine to the upper part of the patella, with the orientation being parallel to that of the muscle fibres of the rectus femoris (Figure 1A and 1B). The ground electrode was placed on the spinous process of C7.

Figure 1A - Electrode Positioning during relaxation



Figure 1B - **Electrode Positioning during contraction**

All athletes were subjected to one set of six maximum concentric dynamic contractions of knee extension and six maximum concentric dynamic contractions of knee flexion, starting with extension and alternating between flexion and extension until the sixth flexion. Usually, more than six agonist contractions and six antagonist muscle contractions are used to prove this relationship. However, it seems relevant to analyse the changes that take place when the act of repetitive movement of shooting a ball during a short term occurs (antagonist contraction followed by agonist).

To conduct the test, a Biodex System 4 isokinetic dynamometer was employed to measure peak torque and knee position. The dynamometer chair was adjusted to an angle of 100 degrees between the hip and spine. Additionally, a femoral and pectoral strap was applied to ensure the athlete remained still throughout the test. Athletes were exposed prior to the real test to two maximal flexions and two maximal extensions of the knee on the left lower limb, allowing them to become accustomed to the test.

Each contraction cycle lasted between 900 and 1000 milliseconds, and there were no rest periods between knee flexion and extension. Surface electromyography (SEMG) was employed to quantify the electrical muscle activity of the rectus femoris in both its active and passive phases. The electromyography (EMG) signal was recorded through Bitalino, which is an affordable and open source biosignals platform scientifically validated (Batista et al., 2019). During the non-dominant limb introductory trial test, the electrical activity of the rectus femoris was recorded to verify whether the signal was being successfully captured and to identify any potential sources of noise.

Each of the samples has a dataset of 10585 entries divided between 5 study subjects and each subject analysed had measurements taken on the 2 lower limbs, classified as dominant and non-dominant. The average number of samples for each variable (EMG, Torque and Speed) was 1059 entries in an average time of 10 seconds for each limb. The EMG value was adjusted; in devices such as the Bitalino, there may be a baseline value that needs to be subtracted to adjust the signal. In this case, the baseline is 500 mV, so this value of 500 mV is assumed to be zero and so all the data is reduced by 500 mV. This transformation is necessary to remove the offset introduced by the equipment, allowing the EMG data to correctly reflect muscle activity (Batista et al., 2019). The sampling frequency was set based on the device with the lowest frequency, which was 100 Hz; the device with the highest frequency had a sampling frequency of 1000 Hz and was reduced by simple arithmetic mean. Following the completion of the tests, the mean frequency (Hz) and amplitude (RMS mV) corresponding to each concentric contraction of the rectus femoris during the knee extension movement were calculated.

The MNF is usually calculated with the Fast Fourier Transform (FFT), but for this calculation it is necessary to have a minimum number of samples in the signal, which is 256 samples for a significant spectral analysis. In this study, using SPSS version 26, we were able to calculate the frequency of each EMG signal and, by using the duration of the signal, calculate the frequency in Hz. With the value of the frequency, in number of occurrences and Hz, it was obtained the maximum frequency and the mean frequency with the standard deviation. SPSS, which is a scientific software package created by IBM used for the analysis of statistical data, has a function to calculate the frequency of a set of values; for example, if a value of 150 mV appears in the signal 50 times, SPSS will show in a table one line for the value of 150 mV and place the number 50 in the frequency column for this value. By sorting this table by frequency, it is possible to extract the maximum frequency and the minimum frequency at the top and the bottom of the sorted table. (De Luca et al., 2010; Konrad, 2005).

For the conversion of the absolute number to a Hertz value, and to make the frequency more useful, it is important to know the duration of the evaluated signal in seconds. With this duration, the frequency value should be divided by the duration in seconds (Merletti & Farina, 2016).

With all the frequencies in a table, the Mean Frequency (MNF) of all signals in the table should be the sum of all frequencies divided by the number of lines in the table. With more lines in the table, the lower the

MNF should be, because the table has more different values (mV) and fewer repetitions of the same value (mV). In the case of the EMG signal, the sample rate of BITalino is 1 kHz. (De Luca et al., 2010).

Data Analysis

Peak Torque Variable: refers to the maximum force exerted by the muscle during a contraction.

EMG Variables: RMS - Root Mean Square: a statistical measure used to quantify the amplitude of the EMG signal. EMG Variables: MNF - Mean Frequency: the measure of the average frequency content of the EMG signal. It provides information about the frequency distribution of the power spectrum.

MVC: Maximum Voluntary Contraction - refers to the greatest amount of force that a muscle or group of muscles can produce during a single maximal effort contraction

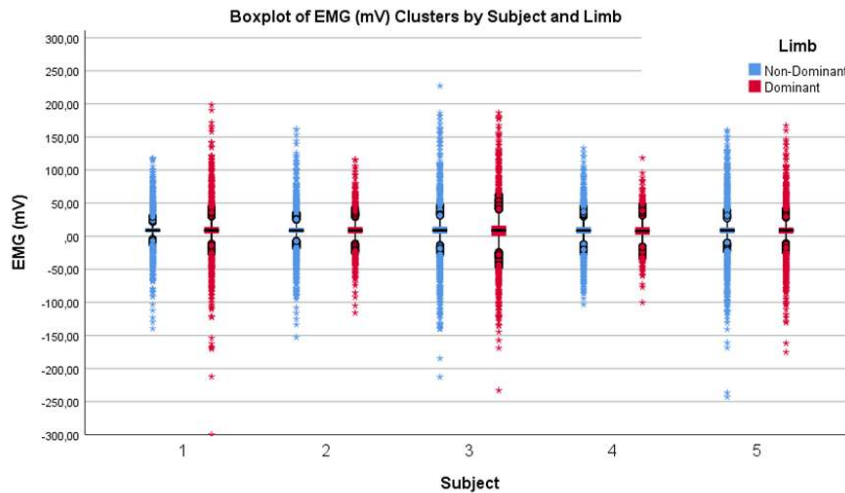
Statistical Analysis

The EMG (mV) and Torque (N-M) samples showed a p-value < 0.001, while the Speed (deg/s) showed a p-value = 0.955, which gives us statistical relevance, since the minimum acceptable for the student's test (T) is ideally 0.05 or 0.075 with reservations.

Results and Discussion

The graphic on Figure 2 is based on the torque output generated by the subjects during the rectus femoris contraction phase by maximum voluntary contraction in relation to the corresponding EMG signal. The red dots and blue dots represent each EMG (mV) value in the dominant leg and non-dominant leg respectively.

Figure 2 – Boxplot of EMG (mV) Clusters by Subject and Limb



We can clearly see that except for subject number 1, all the other athletes had lower variation of their EMG on the dominant leg during MVC, which supports the theory that the dominant leg has increased energy efficiency during a contraction (Farina et al., 2004; Hodges & Bui, 1996; Rainoldi et al., 2004; Soderberg & Knutson, 2000). This can be because the dominant leg usually presents better muscle coordination since it has greater postural control efficiency (Promsri et al., 2023). Another reason may be the fact that in fact, most technical movements in team sports, including ball control, passing, shooting, crossing, and even change of direction duties, appear to be performed by athletes using their dominant leg (Madruga-Parera et al., 2020). Because of this, a greater volume of movements with the dominant leg than with the non-dominant leg is expected, which results in varying degrees of lower limb strength asymmetries (Bishop et al., 2021). There are contradictions in the research that is currently accessible on the cause-effect of these lower limb strength asymmetries, even though they appear to impair players' technical and physical performance (Bishop et al., 2018; Falces Prieto et al., 2019).

Table I presents a correlation analysis between the Torque and EMG variables. Torque and EMG are the main study variables. The Kendall's Tau calculation method indicates a correlation between torque and EMG (with $p < 0.05$). Kendall's tau is commonly used as a distribution-free measure of cross-correlation between two variables (Arndt et al., 1999).

Table I - Correlation analysis

		Torque (N-M)
Kendall's tau_b	EMG (mV)	Correlation Coefficient
		0,013*
		Sig. (2 extremities)
		0,049

Sig.(2 extremities) = p-value < 0,05 (statistically significant);

The asterisk indicates that the correlation is significant at the 0.05 level (2-tailed).

A Kendall's Tau value of 0.013 demonstrates a moderate correlation between the variables measured. In other words, it can be stated that variations in torque are positively related to variations in energy activity in the

muscle. On Table II, we can interpret the values between EMG Dominant vs Non-Dominant limbs. We can evaluate the standard deviation to define that there is a greater variation in the signal of subject 1's dominant limb, so his energy interval is also greater, and we can therefore conclude that he used more energy in activating the muscle of the dominant limb than the non-dominant limb. Subject 2's EMG max and variation is greater in the non-dominant limb: this is the opposite of what is seen in subject 1, and the cause could be because the dominant limb is more efficient. Subject 3, very similar signal for both limbs and the variation and average of both limbs, which supports the possibility that he may be ambidextrous. Subject 4 also appeared to have similar values, although the non-dominant limb had a higher max EMG, because he probably needed less energy in the contraction of the dominant limb. Subject 5, on the other hand, despite having a higher EMG max in the dominant limb, has a greater energy variation in the non-dominant limb than in the dominant limb.

Table II - EMG Dominant vs Non-Dominant

			EMG (mV)						
			Sample	Mean	SD	Maximum	Minimum	Interval	RMS
Subject	1	Non-Dominant	1046	8,77	27,90	118,10	-139,50	257,60	29,23
		Dominant	989	8,80	41,68	198,50	-300,10	498,60	42,57
	2	Non-Dominant	1160	8,68	30,91	161,70	-152,70	314,40	32,09
		Dominant	1113	8,72	22,60	115,90	-115,80	231,70	24,22
	3	Non-Dominant	1073	8,79	44,33	227,20	-212,80	440,00	45,17
		Dominant	1036	8,75	44,54	186,40	-233,10	419,50	45,37
	4	Non-Dominant	1068	8,61	28,29	133,00	-103,10	236,10	29,56
		Dominant	1028	8,21	19,80	118,30	-100,20	218,50	21,43
	5	Non-Dominant	1108	8,09	39,77	160,40	-243,30	403,70	40,56
		Dominant	964	8,61	36,08	167,40	-175,20	342,60	37,07

SD- standard deviation; RMS- Root Mean Square (amplitude measure); Interval – Difference between the maximum and minimum EMG (mV) values.

So, overall, we can say that the dominant limbs have a lower energy expenditure (lower EMG variation) than the non-dominant limbs, which indicates that the muscle has greater energy efficiency, doing the same work with less energy (Farina et al., 2004; Hodges & Bui, 1996; Rainoldi et al., 2004; Soderberg & Knutson, 2000).

A pattern emerges from the data present on Table III. In S1L, S4L, S5L, S2R, S4R and S5R, we observe a decrease in Peak Torque between the first three and last three contractions, accompanied by an increase in RMS Mean.

Table III - Average peak torque and average RMS of the first 3 contractions and the last 3 for each subject and each limb.

Subject	ID Contraction	Average Peak Torque (Nm)	SD	Average RMS EMG (mV)	SD
1	S1L3B	194,60	9,18	36,17	5,47
	S1L3E	192,97	4,65	40,41	2,32
	S1R3B	191,00	6,24	58,81	9,39
	S1R3E	192,33	2,67	52,61	3,66
2	S2L3B	139,90	6,13	39,64	1,73
	S2L3E	140,17	2,10	46,52	8,92
	S2R3B	190,87	2,67	29,77	5,24
	S2R3E	178,27	2,37	33,01	6,96
3	S3L3B	194,50	12,18	65,12	3,58
	S3L3E	184,73	15,57	59,70	0,64
	S3R3B	183,27	6,82	63,46	10,91
	S3R3E	170,87	12,38	58,12	6,43
4	S4L3B	203,67	9,67	38,43	1,35
	S4L3E	196,53	8,86	40,64	4,37
	S4R3B	190,83	7,98	24,05	2,93
	S4R3E	185,47	3,66	27,81	5,35
5	S5L3B	184,83	8,53	53,61	2,53
	S5L3E	162,63	4,11	58,49	12,48
	S5R3B	180,40	6,60	48,73	7,85
	S5R3E	178,90	5,37	53,10	2,67

P value < 0,001 to the variables Average Peak Torque (Nm) and Average RMS EMG (mV); S– Subject N; L ou R – L (Left) Non-Dominant, R (Right) Dominant; 3B or 3E – First 3 (Begin) or Last 3 (End)

Nevertheless, this phenomenon may not have manifested in all the lower limbs of each athlete due to the influence of external variables. Another pattern that can be observed in the limbs S2R, S4L, S4R, S5R in Table IV is that the mean frequency decreases over time in conjunction with a reduction in peak torque (fatigue) or even when this last one remains unchanged, as is the case with S2L. It is well known that fatigue manifests itself in the EMG signal as an increase in amplitude and a decrease in typical spectral frequencies (De Luca, 1984; Madeleine et al., 2002; Merletti et al., 2002).

Table IV - Average peak torque and mean frequency (MNF) of the first 3 contractions and the last 3 for each subject and each limb

Subject	ID Contraction	Torque (N-M)		Frequência EMG (mV)		
		Average Peak (Nm)	SD	Maximum	MF	SD
1	S1L3B	194,60	9,18	90	23,58	17,77
	S1L3E	192,97	4,65	140	24,13	22,09
	S1R3B	191	6,24	110	18,45	14,74
	S1R3E	192,33	2,67	90	19,39	15,48
2	S2L3B	139,9	6,13	110	24,24	19,77
	S2L3E	140,17	2,1	100	21,34	16,43
	S2R3B	190,87	2,67	150	27,71	22,96
	S2R3E	178,27	2,37	90	27,43	19,55
3	S3L3B	194,5	12,18	60	17,73	10,51
	S3L3E	184,73	15,57	100	17,84	13,18
	S3R3B	183,27	6,82	70	16,96	11,24
	S3R3E	170,87	12,38	120	19,12	15,03
4	S4L3B	203,67	9,67	140	22,2	19,69
	S4L3E	196,53	8,86	100	21,94	15,77
	S4R3B	190,83	7,98	120	32,23	25,45
	S4R3E	185,47	3,66	130	29,81	26,24
5	S5L3B	184,83	8,53	80	18,2	13,26
	S5L3E	162,63	4,11	110	19,12	15,25
	S5R3B	180,4	6,6	60	19,6	12,78
	S5R3E	178,9	5,37	70	17,16	11,3

P value < 0,001 to the variables Average Peak Torque (Nm) and Average RMS EMG (mV); S – Subject; L/R – L (Left) Non-Dominant, R (Right) Dominant; 3B ou 3E – First 3 (Begin) or Last 3 (End)

Conclusions

The study demonstrated a correlation between peak torque, root mean square (RMS) and mean frequency (MNF) during fatiguing exercise, more specifically six MVC contractions and extensions of the knee. Despite the limited resources available, and the relatively few dynamic contractions conducted, a correlation was identified that was comparable to that observed in the literature. We verified that between the first 3 contractions and the last 3 contractions, at the same time as the peak torque decreased (fatigue), the RMS increased and the MNF decreased in approximately 40% (S2R, S4L, S4R, S5R) of the cases. These findings have both theoretical and practical implications. Theoretically, the results provide further insight into neuromuscular fatigue mechanisms, supporting the use of EMG parameters like RMS and MNF as reliable indicators of muscle performance during dynamic tasks. Practically, these patterns could inform the development of fatigue-monitoring systems, particularly through artificial intelligence algorithms capable of predicting fatigue thresholds in real-time. Such advancements could benefit athletic training, rehabilitation, and workplace ergonomics by optimizing performance while reducing the risk of injury due to fatigue.

Furthermore, we observed a pattern of greater energy efficiency in the dominant leg of most participants, as reflected by reduced EMG voltage variability. This finding suggests potential applications in tailored training programs aimed at addressing asymmetries in muscle performance, which could enhance overall neuromuscular efficiency. While the study provides meaningful insights, several limitations must be addressed. The small sample size and dynamic nature of the contractions posed challenges to obtaining consistent EMG readings. Future studies with larger participant pools and refined methodologies are recommended to validate these findings further and explore additional applications in both sports science and clinical rehabilitation.

In conclusion, the correlations identified in this study contribute to our understanding of muscle fatigue and performance, offering a foundation for future innovations in fatigue monitoring and management. By leveraging these insights, it is possible to design more effective, evidence-based interventions across various domains, including healthcare, sports, and occupational safety.

Conflicts of interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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Authors' contributions

Author Gonalo Agostinho and author Michele Rosa have given substantial contributions to the conception or the design of the manuscript, author Mauricio Rosa was involved in the acquisition, analysis and interpretation of the data. Author Hugo Ferreira was responsible for reviewing the manuscript. All authors have participated to drafting the manuscript. All authors read and approved the final version of the manuscript. All authors contributed equally to the manuscript and read and approved the final version of the manuscript.

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