Study on Electromyographic Characteristics of Lower Limb Muscles in Lateral Ankle Sprain Patients Based on Arthrogenic Muscle Inhibition (AMI) Theory

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Abstract: This study investigates the alterations in neuromuscular control of the knee joint following lateral ankle sprain, grounded in the Arthrogenic Muscle Inhibition (AMI) theory. Electromyographic assessments were conducted on the vastus lateralis (VL), vastus medialis (VM), semitendinosus (ST), and biceps femoris (BF) muscles. Signal extraction and feature analyses were performed to elucidate the underlying neuromuscular modifications. The findings indicate: 1) unilateral ankle sprains precipitate neural inhibition in adjacent knee joint musculature, consistent with the AMI framework; 2) the injured side exhibits significantly lower RMS max, RMS mean, and integrated EMG (iEMG) values compared to the healthy side, reflecting diminished peak and average muscle activation, reduced muscular stability, and decreased overall work output; 3) post-injury, the injured-side BF and ST muscles manifest pronounced inhibitory suppression and a decline in total work capacity, indicating a predisposition toward accelerated muscular fatigue.

Keywords: Lateral Ankle Sprain; Lower Limb Musculature; Knee Joint; Electromyography

1. Research Background and Significance

Globally, the incidence of sports-related joint injuries is steadily escalating, with ankle sprains ranking among the most prevalent afflictions. The lateral ankle sprain occurrence rate is reported at 4.61 per 10,000 athletes [1], while professional football players exhibit a recurrence rate as high as 51.3% [2]. Investigations encompassing 2,175 athletes across 12 sports have revealed a 68.5% recurrence rate of lateral ankle sprains [3]. Electromyography (EMG), referring to the bioelectrical activity of muscles, enables the assessment of muscle activation levels and fatigue through bioelectrical signal acquisition. To date, EMG research related to ankle sprains has predominantly focused on the calf musculature. For instance, Mendez-Rebolledo et al. [4] discovered that, prior to heel strike, the root mean square (RMS) of the tibialis anterior in individuals with chronic ankle instability (CAI) was significantly lower compared to healthy controls, whereas activation of the peroneus longus was elevated, presumably to correct ankle positioning upon ground contact. Similarly, Altun et al. [5] identified neuromuscular impairments in the peroneal muscles during unilateral stance. Labanca et al. [6] demonstrated delayed activation of the peroneus longus in CAI patients.

According to the Arthrogenic Muscle Inhibition (AMI) theory [7], joint injury, pain, and inflammation trigger neural reflex inhibition that suppresses hip muscle activation capacity without causing inherent structural muscle damage. Consequently, when the ankle is injured, musculature in adjacent regions such as the thigh may also be affected. Existing research on adjacent joints remains limited, predominantly addressing diminished muscle strength in the gluteal and knee flexor-extensor groups post-ankle sprain or emphasizing augmenting muscle strength to enhance ankle stability. For example, CAI patients exhibit significant abnormalities in maximal and submaximal isometric strength of knee flexors and extensors [8]. Additionally, the relative contribution of the gluteus maximus in CAI individuals is notably higher than that of healthy controls, whereas the vastus lateralis holds greater relative weight in healthy subjects compared to those with CAI [9]. Moreover, athletes with a history of lateral ankle sprain display persistent deficits in range of motion, dynamic balance, and neuromuscular control [10]. However, there is a paucity of detailed investigations focusing on the core knee musculature of the lower limb following lateral ankle sprain, especially regarding muscle activation intensity, fatigue resistance, and in-depth neuromuscular control metrics. Bilateral paired-control studies are lacking, impeding definitive conclusions about the differentiated impact of lateral ankle sprain on various functional muscle groups around the knee joint.

The vastus lateralis (VL), vastus medialis (VM), semitendinosus (ST), and biceps femoris (BF) represent the principal musculature of the thigh. VL and VM compose the knee extensor group. Selecting these four muscles forms a comprehensive evaluative circuit, enabling a holistic EMG assessment from sagittal and frontal planes, encompassing anterior-posterior knee joint functions as well as medial-lateral stability. Anterior stability (knee extension): VM, VL; posterior stability (knee flexion/deceleration): BF, ST; frontal plane stability (valgus prevention): VM (emphasized); rotational stability: ST (emphasized).

This study aims to: 1) elucidate the effects of unilateral lateral ankle sprain on the activation level, functional capacity, fatigue resistance, and contraction stability of muscles surrounding the knee joint; 2) verify the extended applicability of the AMI theory within the lower limb kinetic chain; 3) provide a theoretical foundation and practical guidance for comprehensive lower limb rehabilitation and injury prevention post lateral ankle sprain.

2. Subjects and Methods

2.1 Subjects

Electromyographic characteristics of principal lower limb muscles in individuals with lateral ankle sprain.

2.2 Methods

2.2.1 Literature Review

A comprehensive search was conducted through libraries and academic journal databases using keywords such as “Arthrogenic Muscle Inhibition (AMI)”, “lateral ankle sprain”, and “electromyography.” Relevant articles were reviewed to establish the theoretical foundation for experimental design, indicator selection, and content analysis in this study.

2.2.2 Experimental Procedures

(1) Selection of Participants

Eight individuals with unilateral ankle sprain were enrolled as research subjects. All participants were thoroughly informed about the study’s purpose, testing procedures, and potential risks, and completed the Cumberland Ankle Instability Tool (CAIT) questionnaire along with informed consent forms.

Inclusion criteria: (1) Clinically diagnosed unilateral ankle sprain; (2) Post-injury swelling and pain affecting daily activities for no less than three days; (3) Holders of a national Level 2 athlete certification, with training frequency of at least three sessions per week; (4) Signed informed consent; (5) No prior involvement in similar experiments or rehabilitation treatments.

Exclusion criteria: (1) History of bilateral ankle sprains; (2) Previous knee joint injuries or pain; (3) Neuromuscular disorders; (4) Lower limb surgery within the past three months; (5) Inability to cooperate with EMG data collection; (6) Engagement in alcohol consumption, sleep deprivation, or vigorous exercise within 24 hours prior to testing that could affect results.

(2) Participant Demographics

All subjects were male Level 2 national athletes with an average age of 21.37 years, height of 181 cm, weight of 75.5 kg, and injury onset approximately 5.5 months prior. Detailed characteristics are presented in Table 1.

Table 1. Participant Baseline Characteristics (Mean ± SD)

Gender	Age (years)	Height (cm)	Weight (kg)	Time Since Injury (months)
Male	21.37±2.32	181.4±4.57	75.5±6.57	5.5±1.6

(3) Testing Environment and Schedule

The assessments were conducted on November 10, 2025, at the Sports Science Laboratory of Ningde Normal University. Ambient conditions—temperature and climate—were optimal, and all participants exhibited good physical status (RPE < 10), ensuring cooperative engagement and data reliability throughout testing.

(4) Equipment Selection

Surface electromyography signals were acquired using the VISHEE surface EMG system equipped with CH5766GD3 disposable triple-electrode patches. Ancillary materials included alcohol swabs, cotton gauze, and razors for skin preparation.

Parameters: Sampling frequency was set at 1000 Hz, bandwidth ranged from 20 to 500 Hz, and a 50 Hz notch filter was applied to eliminate power line interference. Signals were amplified 1000-fold.

(5) Electrode Placement

Electrodes were positioned bilaterally over the VM, VL, BF, and ST muscles. Placement adhered to the guidelines outlined in the *Application of Surface Electromyography in Sports Medicine*, with electrode centers aligned over muscle bellies and oriented parallel to muscle fiber direction.

(6) Testing Procedure

Pre-test preparation: Participants' inclusion and exclusion criteria were meticulously re-verified to ensure their physiological status met the testing prerequisites. Each subject received comprehensive pre-test training, during which standardized instructions regarding movement execution and key precautions were conveyed to guarantee uniformity of test maneuvers. Essential anthropometric data—name, gender, age, height, weight, and time since injury—were measured and documented. All operations strictly adhered to the manufacturer's surface EMG device manual. Testing was immediately suspended should any discomfort arise, in order to prevent significant data inaccuracies.

Testing process: Upon arrival at the testing site, participants engaged in a standardized 5-minute warm-up regimen designed to mitigate injury risks during assessment. The warm-up comprised 2 minutes of light jogging followed by 3 minutes of dynamic stretching targeting the quadriceps and hamstrings. All warm-up routines were uniformly demonstrated and supervised by the research team. Skin preparation involved cleansing electrode sites with 75% ethanol using cotton swabs and shaving any hair as needed; electrodes were affixed once the skin was thoroughly dry, with centers positioned over the muscle belly aligned parallel to the muscle fiber orientation.

Maximal voluntary isometric contraction (MVC) testing was conducted as follows: VM and VL muscles were assessed in a seated posture with hips and knees flexed at 90°, lower legs naturally hanging, while the researcher applied consistent resistance at the distal tibia. BF and ST muscles were evaluated in the prone position, hips extended, knees flexed to 90°, with steady resistance applied at the Achilles tendon. Each MVC contraction lasted for 5 seconds followed by a 60-second relaxation interval, repeated thrice.

Post-test processing: EMG signals were standardized utilizing the SA7550 surface EMG analysis software to eliminate inter-individual variability inherent in absolute EMG values. The following core EMG feature parameters were extracted for subsequent analysis: peak root mean square (RMS max), mean root mean square (RMS mean), median frequency (MF), integrated electromyography (iEMG), and average coefficient of variation (CV%).

2.2.3 Statistical Analysis

Data were compiled and analyzed using SPSS version 26.0. Measurement data were expressed as mean ± standard deviation (Mean ± SD). A paired-sample t-test was employed to compare EMG indicators between the injured and healthy limbs, thereby providing empirical support for this investigation.

3. Research Findings

3.1 Inhibition of Muscle Activatio

RMS max reflects the peak activation intensity of muscle fibers, whereas RMS mean characterizes the average level of muscle activation. As delineated in Table 2, the injured limb exhibited consistently lower peak and mean activation across all assessed muscles relative to the contralateral healthy side. Notably, the RMS max of the biceps femoris (BF) demonstrated a statistically significant reduction on the injured side compared to the healthy side ($P < 0.05$), as illustrated in Figure 1. Similarly, RMS mean values for BF and semitendinosus (ST) muscles revealed significant disparities between injured and healthy sides ($P < 0.05$), as shown in Figure 2. The greatest percentage difference between limbs was observed in BF, followed by ST, with BF exhibiting the lowest RMS mean, succeeded by ST.

Table 2. Comparison of RMS Values (μV)

Muscle Location	Limb	RMS max (Mean ± SD)	Difference (%)	RMS mean (Mean ± SD)	Difference (%)
VM	Injured	856.32±142.57	-4.72	201.45±35.68	-6.69
	Healthy	898.76±135.24		215.89±32.17	

VL	Injured	892.45±138.76	-2.64	218.76±38.45	-2.92
	Healthy	915.67±129.34		225.34±36.78	
BF	Injured	789.24±156.32*	-14.36	189.56±41.23*	-14.52
	Healthy	921.57±138.45		221.78±39.56	
ST	Injured	812.35±162.45	-8.48	195.67±43.89*	-10.63
	Healthy	887.65±145.32		218.95±40.21	

Note: “*” denotes statistically significant difference; “**” denotes highly significant difference

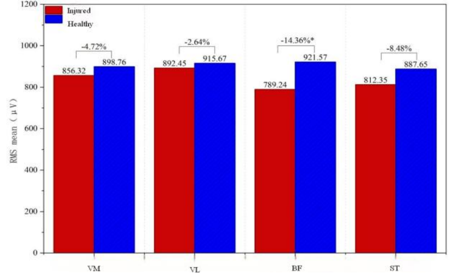

Figure 1. Comparison of RMS max

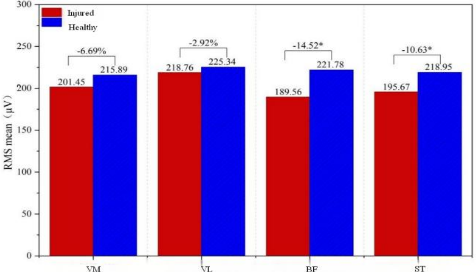

Figure 2. Comparison of RMS mean

3.2 Significant Decline in Total Muscle Work

Integrated EMG (iEMG) represents the cumulative muscular work performed over the measured time frame. The results revealed significant reductions in iEMG values for the biceps femoris (BF) and semitendinosus (ST) on the injured side compared to the healthy side ($P < 0.05$), as demonstrated in Table 3 and Figure 3.

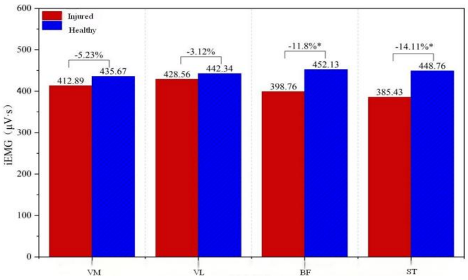

Figure 3. Comparison of iEMG

3.3 Trend of Decreased Median Frequency

Median frequency (MF) serves as an indicator of muscular fatigue, with lower values signifying greater fatigue. Although the injured side consistently displayed reduced MF values compared to the healthy side, no statistically significant differences emerged (see Table 4). Fatigue levels were uniformly higher on the injured side across all muscles. Notably, both injured and healthy sides exhibited lower MF in BF and ST relative to VM and VL, as illustrated in Figure 4.

Table 3. Comparison of Integrated EMG (iEMG) Values (μV · s)

Muscle Location	Limb	Mean±SD	Difference (%)
VM	Injured	412.89±68.32	-5.23
	Healthy	435.67±62.45	
VL	Injured	428.56±71.23	-3.12
	Healthy	442.34±68.56	
BF	Injured	398.76±75.45*	-11.8
	Healthy	452.13±70.89	
ST	Injured	385.43±86.72*	-14.11
	Healthy	448.76±78.32	

Note: “*” denotes statistically significant difference; “**” denotes highly significant difference.

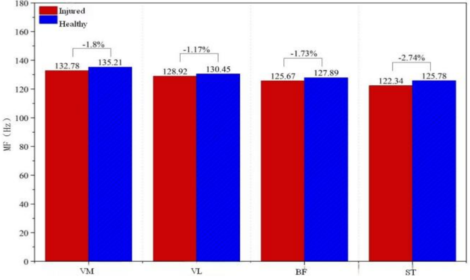

Figure 4. Comparison of Median Frequency (MF)

Table 4. Median Frequency (MF) Comparison (Hz)

Muscle Location	Limb	Mean±SD	Difference (%)
VM	Injured	132.78±19.45	-1.8
	Healthy	135.21±18.76	
VL	Injured	128.92±20.13	-1.17
	Healthy	130.45±19.87	
BF	Injured	125.67±21.34	-1.73
	Healthy	127.89±20.56	

ST	Injured	122.34±22.56	-2.74
	Healthy	125.78±21.34	

Note: “*” denotes statistically significant difference; “**” denotes highly significant difference.

3.4 General Decline in Contraction Stability

Classification of muscle contraction stability based on CV%: CV% < 15% denotes “Good”, 15% ≤ CV% < 20% indicates “Fair”, and CV% ≥ 20% signifies “Needs Attention”. A lower CV% corresponds to greater contraction stability. The analysis revealed that the injured side exhibited elevated CV% across all muscles relative to the healthy side, with the semitendinosus (ST) displaying the highest value of 22.3%, indicating pronounced fluctuations and instability during contraction. Although the biceps femoris (BF) reached 19.4%, categorized as “Fair”, it nonetheless warrants concern (see Table 5).

Table 5. Comparison of Average Coefficient of Variation (CV%)

Muscle Location	Limb	CV%	Stability Assessment	Difference (%)
VM	Injured	16.7	Fair	9.87
	Healthy	15.2	Good	
VL	Injured	17.3	Fair	16.89
	Healthy	14.8	Good	
BF	Injured	19.4	Fair	23.57
	Healthy	15.7	Good	
ST	Injured	22.3	Needs Attention	27.43
	Healthy	17.5	Fair	

4. Discussion

4.1 General Suppression of Electromyographic Activation

The injured side muscles of the lower limb exhibited a comprehensive decline in RMS max, RMS mean, median frequency (MF), and integrated EMG (iEMG) values compared to the healthy side, findings that align closely with the Arthrogenic Muscle Inhibition (AMI) theory. This framework posits that following a joint sprain, even when neighboring joints within the kinetic chain remain unaffected, there occurs a diminished autonomic neural drive and consequent muscle weakness. In cases of lateral ankle sprain, proprioceptors embedded within the joint capsule and ligaments of the ankle are stimulated, potentially disrupting central nervous system signal transmission. The resultant inhibitory effect extends beyond the ankle joint itself; through biomechanical and neurophysiological neural pathways along the lower limb kinetic chain, it adversely influences the musculature surrounding the adjacent knee joint. Previous investigations have confirmed aberrant alterations in knee flexor and extensor strength post ankle sprain; the present study further refines these conclusions by demonstrating a more pronounced inhibitory effect on the knee flexors than the extensors following lateral ankle injuries.

Moreover, the findings underscored a relatively greater suppression magnitude in the biceps femoris (BF) and semitendinosus (ST), evidenced by reductions in peak activation, mean activation, and overall muscular work output. Such impairments compromise the flexor function of the lower limb and its capacity to prevent anterior tibial translation and maintain joint stability. This phenomenon—characterized by “high load yet low activation”—may elevate the risk for anterior cruciate ligament (ACL) injuries, patellofemoral pain syndrome, and meniscal lesions.

4.2 Median Frequency (MF) Shift and Fatigue Implications

Although no statistically significant differences in MF were detected between injured and healthy sides, the injured side consistently manifested lower MF values. A shift toward lower MF frequencies is typically indicative of increased muscular fatigue. In conjunction with diminished RMS max, mean, and iEMG values, this tendency suggests that post lateral ankle sprain, the affected musculature may experience heightened metabolic demands and fatigue susceptibility despite reduced activation. Two possible explanations arise: first, in response to joint instability, the neuromuscular control system adapts by modifying motor unit recruitment order and synchrony, thereby augmenting metabolic load and fatigue risk on the injured side; second, given that maximal voluntary contraction (MVC) was assessed over relatively brief durations insufficient to induce significant fatigue, and considering that subjects were approximately 5.5 months post-injury—at the cusp of transitioning from acute to chronic phases—this may account for the absence of statistically significant MF disparities bilaterally.

4.3 Decline in Joint Stability

An elevation in the coefficient of variation

(CV%) emerged as one of the most salient features on the injured side following lateral ankle sprain. The CV% reflects the temporal synchrony of motor unit firing and the stability of activation patterns. The pervasive increase in CV% on the injured side suggests disruption of central neural transmissions post-injury, leading to a breakdown in the coordinated and fluid neuromuscular activation landscape, as evidenced by heightened signal variability. Furthermore, data revealed an imbalance between knee extensors (vastus medialis and lateralis) and flexors (biceps femoris and semitendinosus), with the extensors exhibiting relatively greater activation and lower CV%, whereas flexors demonstrated reduced activation paired with higher variability. The semitendinosus, a principal internal rotator and stabilizer of the knee, exhibited markedly impaired contraction stability, which may exacerbate aberrant lower limb rotational control—a critical neural mechanism underpinning the increased susceptibility to knee joint injuries following lateral ankle sprain.

5. Conclusions

In summary, through a paired-control study design, this research systematically analyzed the surface electromyographic characteristics of four principal muscle groups surrounding the knee joint following unilateral lateral ankle sprain, yielding the following conclusions:

(1) Unilateral ankle sprain induces neural inhibition of the musculature adjacent to the ipsilateral knee joint, corroborating the Arthrogenic Muscle Inhibition (AMI) theory. The knee flexor muscles exhibit the most pronounced impairment, whereas knee extensors remain relatively unaffected.

(2) Significant differences ($P<0.05$) were observed in the biceps femoris (BF) of the injured limb compared to the healthy side regarding peak activation intensity, mean activation level, and overall muscular work. Similarly, the semitendinosus (ST) demonstrated significant reductions in mean activation and total work output. These findings indicate a marked suppression of activation and diminished functional capacity in BF and ST following lateral ankle sprain.

(3) The peak and mean activation levels, as well as total muscular work of the vastus lateralis (VL), vastus medialis (VM), ST, and BF on the injured side were lower than those of the healthy side, with the lowest values detected in BF and ST.

(4) The coefficient of variation (CV%) was higher on the injured side across all muscles, with the greatest disparities seen in BF and ST, indicating reduced muscular stability post-injury, particularly within these two flexors.

(5) Median frequency (MF) values were diminished on the injured side relative to the healthy side, suggesting an increased propensity toward muscular fatigue in the lower limb consequent to lateral ankle sprain.

Acknowledgments

This work was financially supported by the Fujian Provincial Department of Education's Research Project for Young and Middle-aged Teachers (Grant No. JAT220394).

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