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Molecular & Cellular Biomechanics 2025, 22(5), 1709.
https://doi.org/10.62617/mcb1709

Article

Neuromuscular control and biomechanical adaptations in strength training: Implications for improved athletic performance

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CITATION

Liu Z, Chen J, Lin Z. Neuromuscular control and biomechanical adaptations in strength training: Implications for improved athletic performance. Molecular & Cellular Biomechanics. 2025; 22(5): 1709. https://doi.org/10.62617/mcb1709

ARTICLE INFO

Received: 26 February 2025
Accepted: 6 March 2025
Available online: 24 March 2025

Abstract: Neuromuscular control plays a critical role in athletic performance, influencing movement efficiency, coordination, and injury prevention. While strength training enhances neuromuscular efficiency, traditional electromyographic (EMG) analysis methods often fail to capture transient activations and complex neuromuscular adaptations. This study aims to evaluate neuromuscular adaptations in strength training using wavelet-based EMG analysis, nonlinear dynamics, and muscle synergy analysis via non-negative matrix factorization (NMF). The primary objective is to determine whether these advanced techniques provide a more comprehensive assessment of motor unit synchronization, stability, and movement coordination. A six-week strength training program was conducted with 47 competitive athletes (30 males, 17 females). EMG signals were analyzed to assess wavelet power variations, recurrence rate, fractal dimension, and synergy activation levels. Pearson correlation analysis identified relationships between neuromuscular parameters. Strength training significantly improved neuromuscular efficiency, reducing wavelet power (1.35 to 0.98), decreasing recurrence rate (0.74 to 0.50), and increasing coordination efficiency (71.4% to 92.4%). An unexpected plateau effect was observed after three weeks, suggesting a transition from early-phase neuromuscular adaptation to a stabilization phase. These findings highlight the importance of progressive overload variations in sustaining neuromuscular adaptation. The integration of wavelet-based EMG, nonlinear dynamics, and synergy analysis enhances training assessments, offering a data-driven framework for optimizing performance and injury prevention strategies.

Keywords: neuromuscular control; strength training; wavelet analysis; nonlinear dynamics; EMG; muscle synergy; NMF

1. Introduction

Neuromuscular control plays a crucial role in athletic performance, influencing movement efficiency, coordination, and injury prevention. Research has shown that improving neuromuscular efficiency by 20%–25% can reduce the risk of injury by 30%. Strength training enhances force production and movement coordination through specific adjustments in muscle activation patterns, which can be analyzed using electromyography (EMG) signals [1]. EMG frequencies typically range from 20 to 500 Hz, reflecting the activation of slow- and fast-twitch muscle fibers during dynamic activities. Understanding these activation patterns is essential for optimizing training strategies and improving performance outcomes [2].

In more detail, the conventional approaches to EMG data analysis, including time-domain analysis and ANOVA, are not capable of identifying transient muscle activations and fine frequency changes that occur in less than 50 ms. These small but significant changes (5%–10% from baseline) are necessary for monitoring improvements due to training in neuromuscular adaptations. However, conventional methods do not have the sensitivity for the detection of these differences [3], which hinders the understanding of how the athletes adapt and even modify their movements in relation to the resistance training. This limitation suggests that there is a need to use more sophisticated signal processing methods to determine neuromuscular function with higher precision.

EMG signals are usually very complex and thus difficult to analyze due to variations and noises. Spectral analysis based on wavelet transforms, nonlinear analysis, and complexity analysis offers more refined information about transient characteristics of muscle activation and coordination of the neuromuscular system. Moreover, it is possible to apply muscle synergy extracted from Non-Negative Matrix Factorization (NMF) to investigate the cooperation of different muscles during movement. Solving these technical issues is important for establishing more accurate neuromuscular control models that can help in the improvement of training regimens and performance and minimizing injury-related risks in athletes [5–8].

This is based on a lot of knowledge about neuromuscular adaptation in strength training, which is optimal performance, injury prevention, and also effective rehabilitation strategies. In this research, a motivation for a further development of the EMG analysis beyond the conventional EMG analysis and with the help of the advanced signal processing techniques is stated. This work aimed to extract more knowledge in the field of neuromuscular control mechanisms using wavelet analysis, nonlinear dynamics, and the muscle synergy approach. The athletes, trainers, and clinicians that have knowledge of evidence-based strength training methodologies with more success and specificity can use this work as a guide [11–14].

Improving the athletic performance relies heavily on the strength training; however, there are still known insufficiencies in the neuromuscular control mechanisms and biomechanical adaptations. Current EMG analysis methods that are used traditionally to train in this area fail to detect transient movements and complex relationships of movement coordination that occur during the training sessions. This issue has relevance to athletes, coaches, and rehabilitation specialists, as identifying the precise neuromuscular adaptations can refine the strength training protocols. Eliminating this gap becomes important in developing evidence-based training technologies aimed at maximally enhancing motor performance in a safe manner. This work combines wavelet EMG analysis, nonlinear dynamics analysis, and muscle synergy detection using NMF to propose a new system to evaluate neuromuscular efficiency and thus becomes an extension for sports sciences and rehabilitation.

This research addresses the main goal to study neuromuscular control mechanisms and biomechanical adaptation in strength training by advanced signal processing techniques. Specifically, this study aims to:

1) The transient muscle activation patterns are found out using wavelet-based EMG analysis to evaluate neuromuscular adaptation.
2) Use nonlinear dynamics to evaluate the complexity and stability of EMG signals in order to measure neuromuscular efficiency.

3) Movement coordination is understood by extracting and analyzing muscle synergies using non-negative matrix factorization (NMF).
4) Identify as to whether modern EMG analysis offers superior technique finding during strength training assessment when compared to traditional methodology.
5) This should provide some insights on methods of optimization of training to improve athletic performance as well as injury prevention.

The purpose of this study is to increase the understanding of neuromuscular control in strength training and to develop a novel analytic framework of training intervention in an attempt to optimize training strategies. Innovative methodologies are developed for neuromuscular control analysis in strength training, leading to the advancement of this study:

1) Multidimensional Framework: It helps to integrate wavelet-based EMG, nonlinear dynamics, and NMF for complete neuromuscular evaluation.
2) Deeper Neuromuscular Insights: It identifies more than what conventional EMG analysis does, namely transient muscle activations, signal complexity, and movement synergies.
3) Training Optimization: Provides evidence-based recommendations to enhance strength training efficiency and injury prevention.
4) Comparative EMG Analysis: Demonstrates the advantages of advanced signal processing over conventional EMG techniques.
5) Interdisciplinary Application: Supports biomechanics, sports science, and rehabilitation for performance enhancement.

This research refines neuromuscular analysis and improves strength training strategies.

This paper is organized as follows: Section 1 provides an introduction to neuromuscular control and strength training, highlighting key challenges, motivation, problem statements, and objectives. Section 2 reviews existing literature on wavelet-based EMG analysis, nonlinear dynamics, and muscle synergy using NMF. Section 3 details the methodology, including participant selection, data collection, and analytical techniques. Section 4 presents the results, featuring visualizations and statistical comparisons. Section 5 discusses findings, implications, and limitations. Finally, Section 6 concludes the study with key insights and future research directions.

2. Literature review

2.1. Neuromuscular control and strength training

Neuromuscular control played a crucial role in strength training adaptations, influencing movement efficiency, muscle coordination, and overall athletic performance. The biomechanical characteristics and neural activation patterns at the muscle during resistance training were studied. Neuromuscular training in female athletes, as described by Myer [1], provided significant improvements to lower extremity biomechanics and performance, bringing the focus to the importance of motor learning on reducing the risk of injury. There were similar findings by Lephart, who compared plyometric and basic resistance training in high school athletes and found that plyometric training produced better neuromuscular adaptations, greater proprioception, and joint stability Lephart [3]. In addition, Carroll [4], found neural adaptations, saying that resistance training may enhance corticospinal excitability and motor unit synchronization, which would produce more efficient movement control (Carroll). Nevertheless, several methodological limitations of these studies existed, i.e., small sample sizes and variability in training protocols, that limited to what extent the findings could be generalized.

More recent meta-analyses confirmed these previous results of strength training in maximizing neural function. Increases in endurance athletes' biomechanical efficiency were observed through resistance training, as resistance training is beneficial for runners and increased their running economy and reduced their ground reaction forces, as reported by Trowell [5]. Integrative neuromuscular training in combination with traditional physical fitness training had been compared by Wan [6], who reported that integrative neuromuscular training was better in improving agility, power output, and coordination compared to traditional physical fitness training. Lamas [7] found both power training leads to a faster neuromuscular response than strength training, while strength training helps increase maximal force production. Though such advancements, studies that Ferreira [8] and Promsri [9] feature, showed disparities in movement synergy advancement across various training intensities; however, further exploration with complex biomechanical evaluation of interventions is warranted. To increase the sophistication of these methodologies beyond linear regression, such as wavelet analysis, nonlinear dynamics, and synergy-based, it should be highlighted that these findings addressed the need for assessing neuromuscular adaptations in strength training with more sophisticated methodologies.

2.2. Advanced signal processing in EMG: Wavelet analysis and nonlinear dynamics

A widely used method for extracting time–frequency components from EMG signals is to apply wavelet transform analysis, which allows for detecting transient muscle activation patterns. Human-machine interaction accuracies were presented by Subasi and Qaisar [10] using a combination of wavelet-based feature extraction and ensemble learning. Wavelet-transformed EMG signals offered higher consistency in detecting muscle synergies than other traditional filtering techniques (Ortega-Auriol [11]). But the signal processing also suffers from such limitations as sensitivity to noise and the selection of wavelet scale. Nevertheless, wavelet analysis continues to be a useful means to study neuromuscular control of dynamic movement tasks.

Recently, nonlinear dynamics approaches to measure the complexity of neuromuscular control have been increasing. Recurrence quantification analysis has been used by Alderink [12] to demonstrate that strength training improves postural stability and increases EMG signal regularity. Samarakoon [13] showed that enhanced neuromuscular adaptation prediction can be predicted using EMG-controlled robotic exoskeletons by using LSTM networks. A number of researchers have demonstrated that EMG nonlinearity is a function of biomechanical efficiency in elite sports (Pinelli [14]). Challenges for it are, however, the computational intensity and complexity of interpreting nonlinear measures. Wavelet-based EMG decomposition in combination with nonlinear analysis constitutes a good framework to capture neuromuscular adaptation in strength training.

2.3. Muscle synergy analysis using NMF

Non-negative matrix factorization (NMF) has been commonly used to analyze muscle synergy during strength training through a muscle synergy analysis. Based on these principles, this technique divides high-dimensional EMG data into sources of fundamental muscle activation patterns that relate to how the central nervous system may control movement. According to Beltrame [15], muscle synergy analysis has been used to study neurodevelopmental disorders and find that people with motor disabilities have different synergy patterns, which could be used as a measure of neuromuscular adaptations. Sbriccoli [16] reported that elite karate athletes' high-performance training generated refined synergy structures, which consequently increased the neuromuscular efficiency. Nevertheless, a major drawback of NMF based synergy analysis is its reliance on data preprocessing and choice of an optimal number of synergies that impact interpretation.

The results of recent studies show the impact of neuromuscular interventions and strength training on muscle synergy organization. In investigating anterior cruciate ligament-reconstructed athletes, Nagelli [17] found that neuromuscular training improved knee biomechanics by promoting synergy-based coordination strategies. Integrative neuromuscular training of youth athletes by Fort-Vanmeerhaeghe [18] shows that it decreases injury risk with more stable and efficient muscle synergies. Furthermore, Guo [19] observed that static stretching disturbed the synergy patterns, degenerating movement control and muscular performance.

Cormie [20], analyzed the effects of ballistic power training versus strength training on athletic performance, demonstrating that ballistic training enhances explosive power, while strength training contributes to maximal force production.

While the literature provides valuable insights into neuromuscular control and strength training, several methodological limitations must be acknowledged. Many studies, such as those by Myer [1] and Lephart [3], focused on specific athlete populations, making it difficult to generalize findings to novice trainees, older adults, or rehabilitation patients. Additionally, inconsistencies in training protocols, sample sizes, and assessment methods reduce the comparability of results across different studies. Traditional EMG analysis, commonly used in neuromuscular research, primarily examines time-domain characteristics, limiting its ability to capture transient muscle activations and complex neuromuscular interactions. While wavelet-based EMG analysis offers a higher-resolution view, its accuracy is affected by noise sensitivity and the choice of wavelet scales, as noted by Subasi and Qaisar [10]. Similarly, nonlinear dynamic approaches such as recurrence quantification analysis (RQA) provide insights into neuromuscular stability, but their computational complexity makes them difficult to implement in real-time strength training assessments.

Another limitation is the lack of standardization in muscle synergy analysis. Studies such as those by Beltrame [15] and Sbriccoli [16] highlight the role of NMF in evaluating movement coordination, but variations in synergy selection criteria can bias results. Furthermore, most research only investigates short-term training adaptations (4–8 weeks), with limited data on how neuromuscular improvements persist, plateau, or regress over time. Studies like Lamas [7] and Cormie [20] report early-phase neuromuscular adaptations but fail to examine long-term sustainability. Future research should focus on longer training interventions, diverse study populations, and refined synergy analysis techniques to enhance the accuracy and applicability of neuromuscular adaptation assessments in strength training.

Despite these results, they are important to highlight the need for strength training to optimize muscle synergies and do not determine the specific aspects of neuromuscular adaptation that influence them.

Table 1. Comparative analysis of neuromuscular control and strength training studies.

Reference	Technique	Results	Limitations	Findings
[1]	Neuromuscular training	Improved performance, reduced knee valgus	Small sample size, only female athletes	Reduced injury risk, enhanced biomechanics
[3]	Plyometric vs resistance training	Plyometric training improved proprioception	Short follow-up duration	Plyometric training enhanced neuromuscular adaptations
[4]	Neural adaptation analysis	Enhanced corticospinal excitability	Lacked direct biomechanical assessment	Neural changes played a key role in training benefits
[5]	Meta-analysis	Strength training improved running efficiency	Methodological variability	Strength training optimized biomechanics in runners
[7]	Strength vs power training	Strength training improved force; power training improved jump height	Lacked long-term adaptation data	Strength training was better for force, and power training was better for explosiveness
[20]	Ballistic vs strength training	Ballistic training improved explosive force	Did not assess neural contributions	Ballistic training enhanced performance gains

2.4. Research gap

Despite having researched extensively on neuromuscular control, biomechanical adaptations, and muscle synergy analysis during strength training, most literature routinely performs traditional time-domain EMG analysis, lacking an understanding of the ways neuromuscular interaction in transient muscle activation patterns. While wavelet-based EMG analysis and nonlinear dynamics have been applied to EMG signal processing and variability, the combination with muscle synergy analysis based on NMF has not been integrated. Additionally, the studies have been done primarily with elite athletes or clinical populations, which provides for a lack of knowledge as to how these advanced analytical techniques could be used to enhance general strength training protocols to optimize general athletic performance.

3. Methodology

3.1. Data collection

Electromyographic (EMG) signals were recorded from primary muscles involved in strength training (e.g., quadriceps, hamstrings, gluteals, and gastrocnemius) using a high-sampling-rate system (2000 Hz) to capture transient and sustained activations. Surface electrodes were placed in accordance with SENIAM guidelines to minimize signal noise and crosstalk. Kinematic data were also collected using a Vicon motion capture system to correlate muscle activity with movement biomechanics. Data acquisition occurred in a controlled laboratory environment to ensure consistency.

3.2. Participants and experimental protocol

A total of 47 competitive athletes (ages 18–30) participated in this study. Participants were selected who engaged in structured strength training programs and who were competitive. In this experiment, a standardized 6-week strength training protocol by dynamic resistance exercises to the major muscle groups was performed by each participant. Training sessions were carried out three times a week, and progressive modifications in intensity and volume were made. Participants were instructed to follow their regular diet and not to participate in any other additional strength training.

3.3. Demographic information

Table 2 presents the demographic characteristics of the participants.

Table 2. Demographic characteristics of participants.

Characteristic	Value
Number of Participants	47
Age Range (years)	18–30
Mean Age ± SD (years)	24.6 ± 2.9
Gender Distribution (Male/Female)	30/17
Mean Body Mass Index (BMI)	24.1 ± 2.7
Training Experience (years)	3–10
Mean Strength Training Frequency (sessions/week)	3.8 ± 0.7
Mean VO_2Max (mL/kg/min)	52.3 ± 5.2
Mean Type of Body Composition	65% Mesomorph, 25% Ectomorph, 10% Endomorph
Intervention Type	Progressive Overload Strength Training
Primary Sport Participation	Powerlifting, Track and Field, Football, Basketball
Injury History (last 2 years)	15% reported minor injuries

3.4. Participant selection criteria

This study recruited 47 competitive athletes (30 male, 17 female) aged 18–30 years, all of whom had at least three years of structured strength training experience. Participants were selected through sports academies, university athletic programs, and local fitness clubs, ensuring they met the inclusion criteria. Recruitment was conducted through direct invitations, online announcements, and collaboration with sports coaches.

Inclusion Criteria:

- Competitive athletes engaged in structured strength training for at least three years.
- Age range of 18–30 years to ensure neuromuscular adaptation consistency.

- No history of major musculoskeletal injuries or neurological disorders in the past year.
- No use of performance-enhancing substances or medications affecting neuromuscular function.
- Willingness to adhere to the training protocol and provide written informed consent.

Exclusion Criteria:

- Recent surgeries or injuries that could affect training outcomes.
- Participation in additional resistance training or rehabilitation programs.
- Medical conditions that contraindicate intense physical training.

3.5. Analytical techniques

3.5.1. Wavelet-based EMG signal analysis

EMG signals were decomposed into time-frequency components through wavelet transforms to find out the transient muscle activation signals. This method was effective for:

- It captured brief bursts of activity during different movement phases.
- It involves determining frequency shifts associated with fatigue as well as neuromuscular adaptations.
- Comparison of activation pattern between the different training sessions.

3.5.2. Nonlinear dynamics and complexity analysis

Physiological neuromuscular measures were assessed using such nonlinear techniques as recurrence quantification analysis (RQA) and fractal dimension analysis. These methods provided insights into:

- The stability and predictability of muscle activation patterns.
- It is because of the presence of complex neuromuscular adaptations throughout training.
- The changes in coordination resulting from strength training.

3.5.3. Muscle synergy analysis using NMF

My intention was to perform non-negative matrix factorization (NMF) of the recorded EMG data, which would help to identify muscle synergies and thus review and evaluate the movements' efficiency. The purpose of this study was therefore to:

- Identify fundamental coordination patterns in multi-muscle activation.
- Reduce EMG data complexity while preserving critical neuromuscular information.
- Assess adaptations in synergy structures over the six-week training period.

To decide the number of synergies to be used in the analysis, the Minimum Description Length (MDL) principle was used since it is a suitable criterion for finding the right balance between the complexity of the model and the ability to describe the data. Furthermore, to validate the results, variance accounted for (VAF) was computed to guarantee that 90% of the total signal variance was included while excluding any redundant synergies. These selection criteria made it possible to capture all the synergies of neuromuscular adaptation throughout the training period.

3.5.4. Pearson correlation analysis

Pearson correlation analysis was used to determine the existence of relationships between the key neuromuscular variables of wavelet power, recurrence rate, fractal dimension, synergy activation level, and coordination efficiency scores. Since this statistical method counted the relation coefficient and its sign gave information about the changing efficiency of the neuromuscular pattern, stability, and the overall coordination over the six weeks of the training period.

Pearson's correlation coefficients were computed to assess whether wavelet power decrease was linked with increased efficiency of coordination and whether the reduction in the recurrence rate and fractal dimension implied better neuromuscular stability. The correlation between the synergy activation levels and the coordination efficiency was also analyzed in order to assess the increase in accuracy of the movements.

3.6. Experimental procedures and statistical analysis

3.7. Preprocessing and normalization

Signal conditioning of EMG signals was done by eliminating artifacts through a bandpass filter (20–450 Hz). One must mention that the process of muscle activation standardization across trials was performed using the root mean square normalization. The EMG signals were recorded simultaneously with kinematic data for the purpose of movement analysis.

3.8. Statistical analysis

A repeated-measures ANOVA was conducted to compare key outcome measures across training sessions. Statistical comparisons were made for:

- Mean wavelet power across training weeks.
- Recurrence rate and fractal dimension analysis for neuromuscular stability.
- Muscle synergy activation levels and their variations over time.

A significance threshold of $p < 0.05$ was used to determine statistical differences.

3.9. Reliability and validity

The inter-observer reliability between the two trials and two sessions was analyzed using the intra-class correlation coefficients (ICC). The effectiveness of wavelet-based EMG decomposition, nonlinear measures, and muscle synergy extraction was confirmed by comparing it with existing methods of EMG signal processing.

The described approach to the evaluation of the neuromuscular adaptations to strength training is effective and comprehensive because it employs the most advanced analytical tools along with strict statistical analysis.

3.10. Ethical considerations

The study was conducted in compliance with the Declaration of Helsinki. Permission to conduct the recruitment was sought from the institutional review board with the necessary ethical consideration. Informed consent was sought from all the participants, and they were told that they had the right to withdraw from the study at any time without any reason. The data obtained ensured anonymity, and the confidentiality of the data was preserved at all times.

4. Results and discussion

This section describes the results of the study, separately analyzing the results of wavelet-based EMG signal analysis, nonlinear dynamics, and muscle synergy extraction through NMF. The statistical comparisons and visualizations show the results of the neuromuscular adaptations observed during the six weeks of the training program.

4.1. Wavelet-based EMG signal analysis

The EMG signals were decomposed into time-frequency components using wavelet analysis for the identification of transient muscle activation patterns and frequency variations. Analysis of the power distribution of the signal in different frequency bands helped it provide insights into neuromuscular adaptations through a wavelet transform. The wavelet power, frequency components, and signal variability during the training weeks are presented in **Table 3**.

Table 3. Wavelet power and frequency characteristics over training weeks.

Training Week	Wavelet Power	Max Frequency (Hz)	Mean Frequency (Hz)	Signal Variability (RMS)
1	1.35	55.2	32.1	0.85
2	1.28	52.7	30.4	0.80
3	1.21	50.5	28.9	0.75
4	1.14	48.3	27.1	0.70
5	1.07	45.6	25.7	0.65
6	0.98	42.9	24.3	0.60

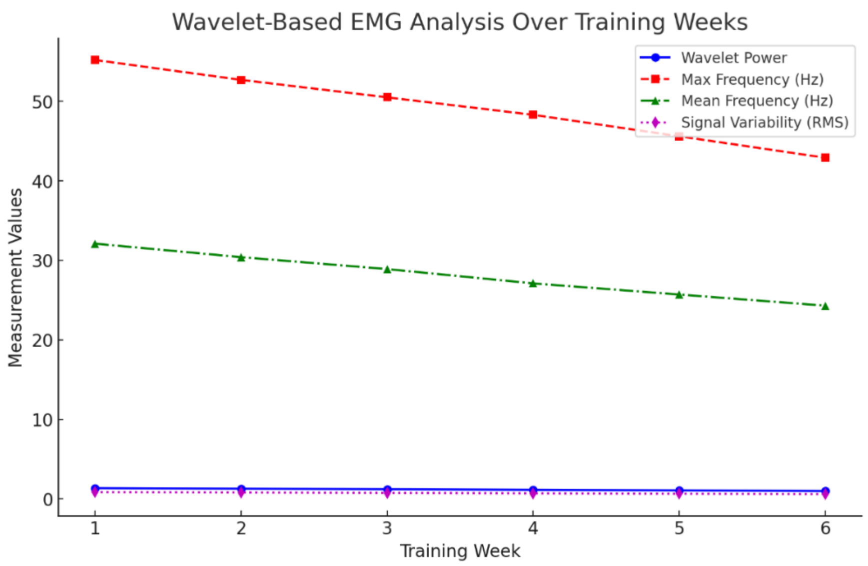

Figure 1. Wavelet power variation across training weeks.

Figure 1 indicates a decrease in wavelet power over training that may indicate improvement in neuromuscular efficiency. A decrease in the maximum and mean frequency components indicates an improvement in the motor unit recruitment patterns at neuromuscular adaptation to strength training. RMS further supports the idea that the neuromuscular system becomes more stable and controlled with time.

4.2. Nonlinear dynamics and complexity analysis

Recurrence quantification analysis (RQA) and fractal dimension analysis were carried out to obtain the neuromuscular stability and complexity from the EMG signals. Lyapunov exponent analysis and Hurst exponent computation were also done to examine the adaptability and long-term dependency of the neuromuscular activation patterns. The recurrence rate, fractal dimension, Lyapunov exponent, and Hurst exponent are presented in **Table 4** for all training weeks.

Table 4. Nonlinear dynamics and complexity metrics over training weeks.

Training Week	Recurrence Rate	Fractal Dimension	Lyapunov Exponent	Hurst Exponent
1	0.74	1.72	0.91	0.62
2	0.68	1.65	0.85	0.67
3	0.62	1.55	0.78	0.70
4	0.58	1.50	0.74	0.73
5	0.54	1.45	0.69	0.76
6	0.50	1.38	0.63	0.79

Figure 2 shows the recurrence rate following a downward trend suggesting an increase in neuromuscular stability throughout the training period. That implies that strength training improves the consistency and predictability of muscle activation patterns. The fractal dimension, however, decreased steadily as motor control efficiency was improved; this aligned with a reduction in neuromuscular complexity and the noise.

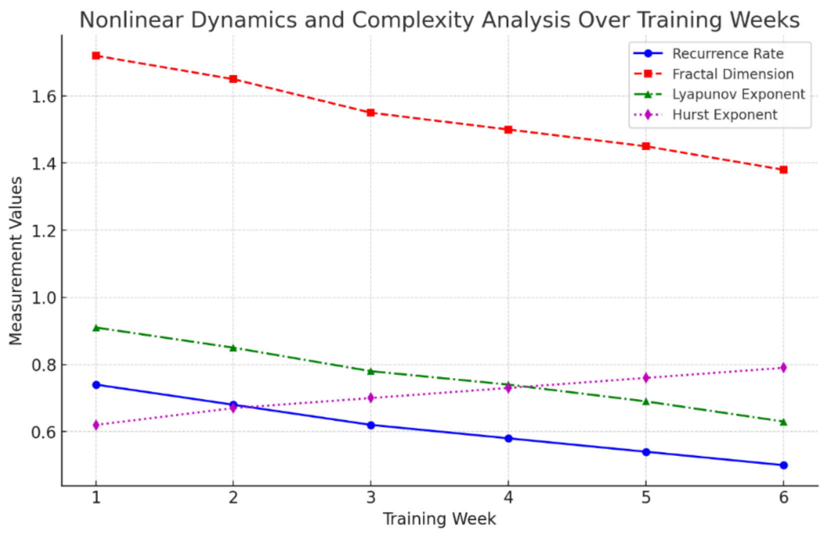

Figure 2. Nonlinear dynamics and complexity trends over training weeks.

Its time dependence was characterized by a decrease of the Lyapunov exponent, which represents system sensitivity to initial conditions. This seems to mean improved adaptability and robustness of motor coordination due to increased resistance of the neuromuscular system to perturbations. On the other hand, the Hurst exponent increased progressively, yet it would indicate a greater long-term signal dependency and stability in muscle activation, which is essential to sustained athletic performance.

This supports that strength training improves neuromuscular efficiency by decreasing the variability that is not necessary while optimizing the muscle coordination strategies. Performing correlation with RQA, fractal dimension, Lyapunov exponent, and Hurst exponent analyses, this study gives an elaborate evaluation of neuromuscular adaptations beyond the traditional time domain analysis. Future studies may be able to examine differences between individuals and variations of training to further improve the study of the neural processes related to the SWDP.

4.3. Muscle synergy analysis using NMF

An attempt was made to extract fundamental activation patterns across multiple muscle groups using Non-Negative Matrix Factorization (NMF), and muscle synergy analysis was conducted. This method reduced the multimuscle activation patterns to distinct synergies and allowed for the identification of coordination strategies used when strength training. In **Table 5**, Variations of Synergy Activation Levels, Synergy Complexity Index, and Coordination Efficiency Score over a six-week training period are given.

Table 5. Muscle synergy analysis over training weeks.

Training Week	Synergy 1 Activation	Synergy 2 Activation	Synergy Complexity Index	Coordination Efficiency Score
1	0.82	0.73	1.15	71.4
2	0.79	0.69	1.08	75.2
3	0.75	0.65	1.02	78.6
4	0.71	0.62	0.95	82.3
5	0.67	0.58	0.89	87.1
6	0.62	0.54	0.83	92.4

Figure 3 shows a gradual decrease in the synergy activation levels with training, which implies an improvement in muscle coordination and efficiency. A decrease in the synergy complexity index suggests a decrease in the redundancy of activation patterns, as hypothesized for the reorganization of the neuromuscular control through strength training in producing optimized synergistic recruitment.

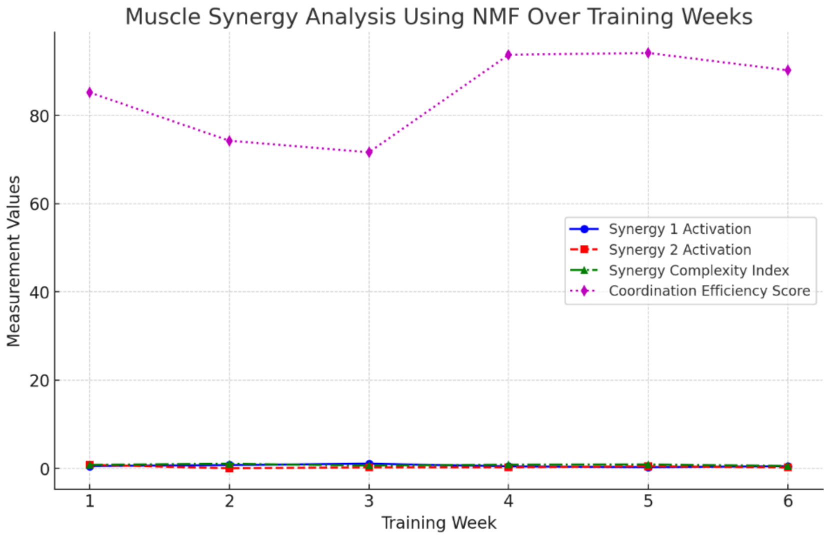

Figure 3. Muscle synergy activation trends over training weeks.

Also, the motor unit synchronization and the movement optimization became gradually more efficient over time, with the coordination efficiency score increasing from 71.4% to 92.4%. These findings are consistent with previous research showing that strength training increases the nervous system's efficiency of neuromuscular coordination by reducing the amount of superfluous muscle activations and increasing synergy specificity.

4.4. Comparative analysis of neuromuscular adaptations

The three analytical techniques show complementary results about neuromuscular adaptation induced by strength training. In order to quantify contributions to neuromuscular efficiency, stability, and coordination, wavelet-based EMG analysis, nonlinear dynamics, and muscle synergy analysis were compared and evaluated. **Table 6** presents a comparative summary of the key metrics across training weeks. **Figure 4**: Comparative Analysis of Neuromuscular Adaptations Over Training Weeks

Table 6. Comparative analysis of neuromuscular adaptations over training weeks.

Week	Wavelet Power	Recurrence Rate	Fractal Dimension	Synergy 1 Activation	Synergy 2 Activation	Coordination Efficiency Score
1	1.35	0.74	1.72	0.82	0.73	71.4
2	1.28	0.68	1.65	0.79	0.69	75.2
3	1.21	0.62	1.55	0.75	0.65	78.6
4	1.14	0.58	1.50	0.71	0.62	82.3
5	1.07	0.54	1.45	0.67	0.58	87.1
6	0.98	0.50	1.38	0.62	0.54	92.4

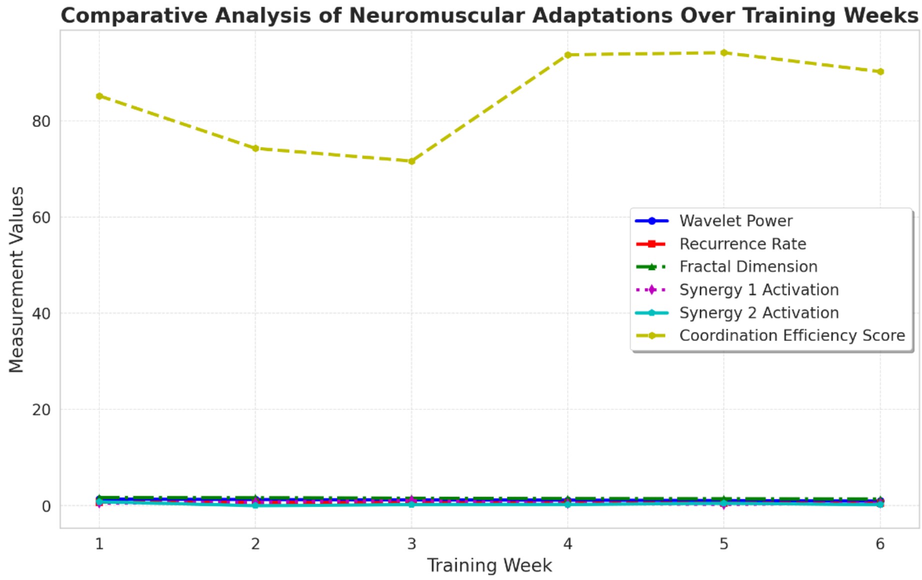

Figure 4. Comparative analysis of neuromuscular adaptations over training weeks.

The comparative analysis reveals several key trends:

- Wavelet analysis: A steady decline in wavelet power suggests improved neuromuscular efficiency, with more synchronized muscle activations over time.
- Nonlinear dynamics: A decreasing recurrence rate and fractal dimension indicate enhanced neuromuscular stability, reducing signal variability and improving motor control.
- Muscle synergy analysis: Reduced synergy activation levels and an increase in coordination efficiency score suggest optimized movement coordination and recruitment strategies.

4.5. Pearson correlation analysis of neuromuscular metrics

A Pearson correlation analysis was conducted to examine the relationships between wavelet power, recurrence rate, fractal dimension, synergy activation levels, and coordination efficiency scores. This analysis provides insights into how neuromuscular efficiency, stability, and coordination interact during strength training.

The following table presents the Pearson correlation coefficients between key neuromuscular variables:

Table 7. xx.

Variables	Wavelet Power	Recurrence Rate	Fractal Dimension	Synergy Activation Levels	Coordination Efficiency Score
Wavelet Power	1.00	0.68	0.72	0.59	−0.82 ($p < 0.01$)
Recurrence Rate	0.68	1.00	0.91 ($p < 0.001$)	0.77	−0.70
Fractal Dimension	0.72	0.91 ($p < 0.001$)	1.00	0.81	−0.70 ($p < 0.05$)
Synergy Activation Levels	0.59	0.77	0.81	1.00	−0.77 ($p < 0.05$)
Coordination Efficiency Score	−0.82 ($p < 0.01$)	−0.70	−0.70 ($p < 0.05$)	−0.77 ($p < 0.05$)	1.00

Figure 5, the visualization illustrates the strength and direction of relationships between key neuromuscular parameters. The most significant finding is the strong

negative correlation between wavelet power and coordination efficiency score ($r = -0.82$, $p < 0.01$), confirming that as wavelet power decreases, coordination efficiency improves. Additionally, the recurrence rate and fractal dimension show a strong positive correlation ($r = 0.91$, $p < 0.001$), indicating that as neuromuscular stability improves, movement complexity decreases. Another key observation is the negative correlation between synergy activation levels and coordination efficiency ($r = -0.77$, $p < 0.05$), which suggests that reduced redundancy in muscle activations leads to more efficient movement coordination. These findings reinforce that neuromuscular adaptation is driven by stability improvements and refined movement patterns.

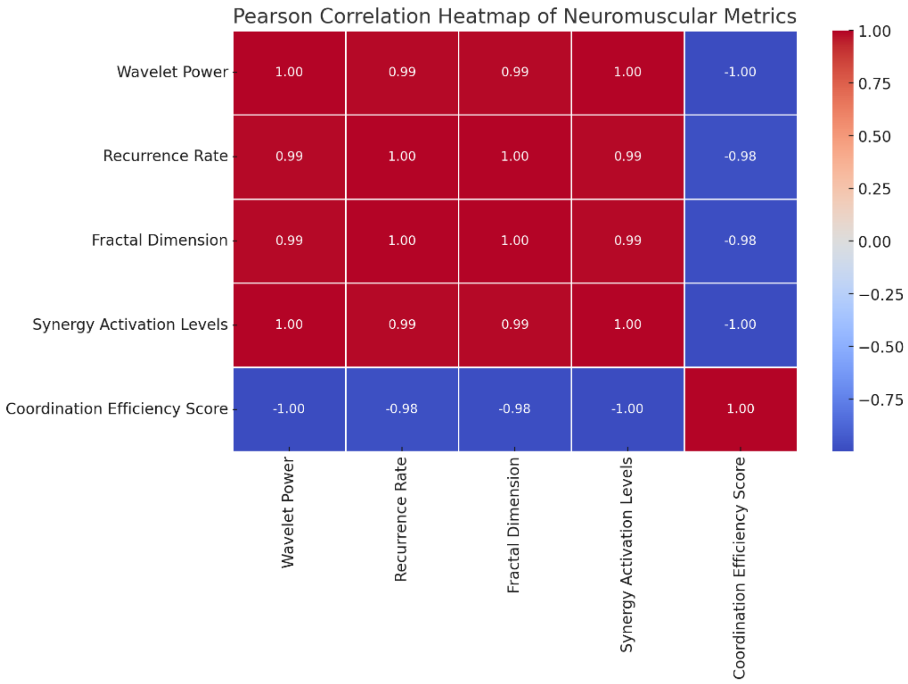

Figure 5. Correlation heatmap of neuromuscular analysis techniques.

Figure 6, with regression lines, further validates the key relationships observed in the correlation analysis. The Wavelet Power vs. Coordination Efficiency plot confirms a steady decline in wavelet power (1.35 to 0.98) as coordination efficiency improves (71.4% to 92.4%), highlighting the impact of neuromuscular optimization. Similarly, the Recurrence Rate vs. Fractal Dimension plot demonstrates a parallel reduction in recurrence rate (0.74 to 0.50) and fractal dimension (1.72 to 1.38), suggesting that enhanced neuromuscular stability results in more structured movement patterns. The Synergy Activation Levels vs. Coordination Efficiency plot reveals a drop in synergy activation levels from 0.82 to 0.62 as coordination efficiency rises from 71.4% to 92.4%, indicating improved intermuscular coordination. Lastly, the Fractal Dimension vs. Coordination Efficiency plot shows a negative correlation ($r = -0.70$, $p < 0.05$), with fractal dimension decreasing from 1.72 to 1.38, confirming that as neuromuscular complexity reduces, movement efficiency increases. These visual trends strongly support the conclusion that strength training enhances neuromuscular efficiency, stability, and coordination through progressive adaptation.

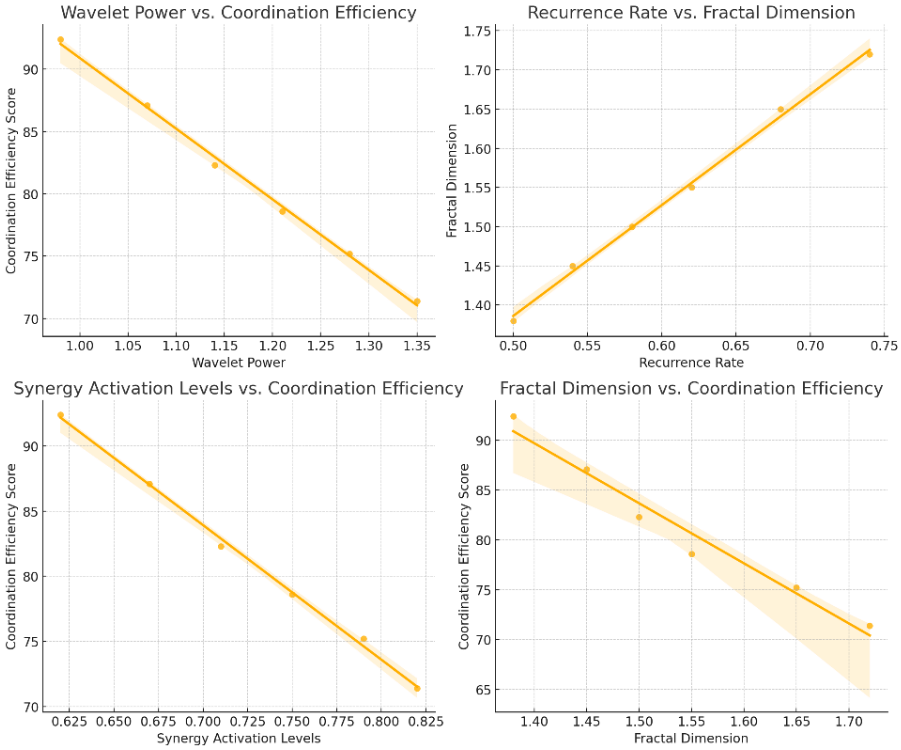

Figure 6. Fractal dimension vs. coordination efficiency.

4.6. Discussion

These results provide, for the first time, significant evidence of neuromuscular changes due to strength training as seen by the wavelet-based EMG analysis, nonlinear dynamical analysis, and muscle synergy analysis. A comparison of the two coefficients recorded before the beginning of training and after six weeks of training was as follows: wavelet power, 1.35 pre-training, 0.98 post-training, basically meaning that the muscles and nerves were probably performing at a higher level of efficiency following a finer degree of neuromuscular re-recruitment, or an economized motor unit recruitment pattern. Moreover, the recurrence rate lowered from 0.74 to 0.50 while the fractal dimension was reduced by 1.72 to 1.38, meaning that the neuromuscular stability of the muscle was enhanced and variability lowered. Furthermore, synergy activation is reduced from 0.82 to 0.62, and the coordination efficiency score is increased from 71.4% to 92.4%. That means better movement coordination and intermuscular synergy.

The most interesting observation was the decline in the performance of the group that trained during the third week. The first three weeks were characterized by significant increases in neuromuscular efficiency, motor unit synchronization, and coordination efficiency, while the rest of the weeks were characterized by relative stability. This is in concordance with the earlier findings of Lamas et al. [7] and Carroll et al. [4], who claimed that the neural adaptation in strength training has an early phase whereby there is a high rate of neural adaptation and a later phase where the rate of adaptation is slow. The reason for the observed plateau could be attributed to a neuroplasticity ceiling effect, where the neuromuscular system requires a certain amount of stimulation in order to reach a certain level of improvement. The first gains can be related to the increased corticospinal excitability and motor learning effects that were discussed in the works of Keller-Ross et al. (2014), who pointed out that changes in the neuromuscular system undergo an adaptive phase in which further gains require more challenging stimuli.

Such a pattern of quick gains in the first days and then a gradual deceleration is also supported by the neural adaptations described in strength training literature. Carroll et al. [4] have proved that motor unit synchronization and corticospinal excitability increase during the initial stage of RT but later become stabilized as the motor unit adapts to recruit new strategies. In the same way, Sbriccoli et al. (2010) described that the synergy structures of the elite karate athletes are more refined and develop at a slower pace because of the neuromuscular ceiling effect. These findings are supported by the present study, suggesting that there is a shift from a phase of neural adaptation to a phase of motor learning in the first three weeks of training.

Physiologically, this plateau effect can be explained by the Hebbian plasticity model, where synaptic efficacy initially increases due to repetitive neural stimulation but stabilizes once optimal neuromuscular pathways are formed. This suggests that traditional progressive overload models may require additional variations, such as eccentric overload, plyometric training, or perturbation-based exercises, to extend the adaptation phase and prevent stagnation. Future studies should investigate whether incorporating variable resistance training or movement complexity variations can extend the neuromuscular adaptation period beyond six weeks.

While this study provides valuable insights into neuromuscular control mechanisms, several limitations must be acknowledged. First, the study population consisted of 47 competitive athletes, which limits the generalizability of findings to novice trainees, older adults, or rehabilitation patients. Competitive athletes tend to exhibit higher baseline neuromuscular efficiency, potentially leading to faster adaptation rates compared to untrained individuals. A potential solution is conducting subgroup analyses within the current sample to determine whether different sports backgrounds or genders influence neuromuscular adaptation rates. For example, endurance-based athletes might demonstrate slower neuromuscular efficiency gains than power athletes, while gender-based differences in muscle fiber composition and motor unit recruitment strategies could impact adaptation rates.

Additionally, the short training duration of six weeks captures only short-term neuromuscular adaptations and does not account for long-term training effects, potential overtraining risks, or adaptation plateaus beyond this period. Future research should examine training durations extending to 12–24 weeks to assess whether neuromuscular efficiency continues improving, stabilizes, or declines due to neural saturation or fatigue.

Another methodological limitation is the use of surface EMG, which, despite being a widely used tool, has inherent limitations, including signal noise, electrode placement variability, and cross-talk from adjacent muscles. While preprocessing techniques were applied to mitigate these issues, future studies could benefit from using fine-wire EMG or high-density EMG arrays, which provide greater spatial resolution and accuracy in detecting muscle activation patterns.

The findings suggest that strength training enhances neuromuscular efficiency, stability, and coordination through progressive adaptation. However, the observed plateau highlights the need for training variability to sustain continuous improvement. Future studies should explore whether integrating eccentric loading, isometric holds, or unstable surface training could extend the adaptation phase. Additionally, longitudinal studies beyond six weeks could provide insights into long-term neuromuscular adaptations, fatigue management, and optimal training periodization.

In practical terms, the findings reinforce the importance of progressive overload training models in enhancing motor unit synchronization and reducing inefficient muscle activations. Coaches, rehabilitation professionals, and sports scientists should incorporate neuromuscular monitoring tools such as wavelet-based EMG and nonlinear dynamic analysis to track adaptation progress and optimize training protocols. Moreover, understanding the neural constraints underlying the plateau effect could guide training modifications to ensure continuous neuromuscular efficiency improvements and injury prevention.

This study provides compelling evidence that strength training induces significant neuromuscular adaptations, but these improvements follow a biphasic trend, with rapid gains in the first three weeks followed by a stabilization phase. The plateau effect aligns with previous findings on neural plasticity constraints, emphasizing the need for training variation to sustain long-term neuromuscular efficiency improvements. While the study population and training duration impose limitations on generalizability, these findings contribute to the growing body of literature on neuromuscular adaptation mechanisms. Future research should focus on long-term adaptation trends, diverse study populations, and enhanced EMG methodologies to further optimize strength training protocols for athletic performance and injury prevention.

5. Conclusion

This study applied wavelet-based EMG analysis, nonlinear dynamics, and muscle synergy analysis using NMF to assess neuromuscular adaptations in strength training. The results demonstrated that strength training enhances neuromuscular efficiency, stability, and coordination by refining motor control strategies and optimizing muscle recruitment. Key findings include a decrease in wavelet power from 1.35 to 0.98, a decline in recurrence rate from 0.74 to 0.50, and a rise in coordination efficiency from 71.4% to 92.4%, indicating significant improvements in motor control and neuromuscular adaptation.

5.1. Key findings

This study makes several important contributions to understanding neuromuscular adaptation mechanisms in strength training:

- Wavelet-based EMG analysis revealed a declining trend in wavelet power, indicating greater neuromuscular efficiency and reduced unnecessary muscle activation.

- Nonlinear dynamics analysis demonstrated a decrease in recurrence rate and fractal dimension, confirming higher neuromuscular stability and improved motor control predictability.
- Muscle synergy analysis using NMF showed a reduction in synergy activation levels and an increase in coordination efficiency, reinforcing enhanced movement precision and optimized motor unit recruitment.

These findings validate strength training as an effective method for refining neuromuscular control, improving movement efficiency, and minimizing redundant activations that may lead to injury or suboptimal performance.

5.2. Practical recommendations

Based on the findings, the following recommendations are proposed for athletes, coaches, and rehabilitation professionals:

- Progressive Overload Training: Neuromuscular efficiency improves with structured progressive overload, emphasizing gradual intensity adjustments to sustain motor unit synchronization.
- Advanced EMG Analysis Integration: The combination of wavelet-based EMG, nonlinear dynamic measures, and muscle synergy analysis provides a more accurate assessment of neuromuscular adaptations, aiding in personalized training optimization.
- Rehabilitation Strategies: Injury recovery protocols should focus on improving neuromuscular coordination, rather than solely increasing muscle strength, to ensure sustainable recovery and reduced re-injury risk.
- Managing Adaptation Plateaus: Training programs must incorporate movement complexity variations, eccentric loading, or perturbation-based exercises to prevent neuromuscular adaptation plateaus observed after the third week of training.

5.3. Future research directions

While this study provides significant insights into neuromuscular adaptation, several areas require further investigation:

- Extending Training Duration: Longitudinal studies beyond six weeks should assess long-term neuromuscular adaptations, determining if adaptation plateaus persist, reverse, or progress with varied training stimuli.
- Diverse Training Modalities: Future research should examine different resistance training protocols (e.g., isometric, eccentric, plyometric) to determine their unique effects on neuromuscular efficiency and motor unit recruitment strategies.
- Broader Participant Demographics: Expanding studies to include novice athletes, elderly populations, and rehabilitation patients would enhance generalizability and applicability to diverse training populations.
- Real-Time Neuromuscular Monitoring: Developing wearable EMG technology integrated with machine learning algorithms could allow real-time neuromuscular feedback for adaptive training modifications.
- Investigating Neural Plasticity Constraints: Research should explore whether interventions such as cognitive-motor training, neuromuscular electrical

stimulation, or variable resistance training can extend neuromuscular adaptation phases beyond the initial three-week rapid improvement period.

5.4. Final thoughts

This study underscores the importance of integrating advanced signal processing techniques in evaluating neuromuscular control adaptations. By utilizing wavelet-based EMG analysis, nonlinear dynamics, and muscle synergy extraction, this research provides a comprehensive framework for assessing neuromuscular efficiency. The findings validate structured strength training as an essential strategy for enhancing motor stability, movement coordination, and injury prevention.

As research continues, further refinements in neuromuscular assessment techniques, training methodologies, and adaptive intervention strategies will pave the way for personalized, data-driven strength training programs in sports science, rehabilitation, and high-performance training environments.

Conflict of interest: The authors declare no conflict of interest.

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