Journal of Rehabilitation Sciences and Research

Journal Home Page: jrsr.sums.ac.ir

Original Article

A Novel Approach to Analyzing Wrestling Skills: Multidimensional Recurrence Quantification Analysis of Muscle Activity

Kazem Esfandiarian-Nasab[1*], PhD; Mansour Eslami[1], PhD; Fateme Salari-Esker[1], PhD; Rohollah Yousefpour[2], PhD

[1] Department of Motor Behavior and Sports Biomechanics, Faculty of Sports Sciences, University of Mazandaran, Mazandaran, Iran.
[2] Department of Computer Sciences, Faculty of Mathematical Sciences, University of Mazandaran, Mazandaran, Iran.

ARTICLE INFO

Article History:
Received: 04/12/2024
Revised: 15/01/2025
Accepted: 26/02/2025

Keywords:
Motor Patterns
Adaptability
Stability
Multidimensional Recurrence Quantification Analysis (MDRQA)
Wrestling
Complexity

Please cite this article as:
Esfandiarian-Nasab K, Eslami M, Salari-Esker F, Yousefpour R. A Novel Approach to Analyzing Wrestling Skills: Multidimensional Recurrence Quantification Analysis of Muscle Activity. JRSR. 2026;13(1):68-74. doi: 10.30476/jrsr.2025.105002.1539

ABSTRACT

Background: As athletes develop, their motor patterns evolve from variable to adaptive neuromuscular control strategies, enabling precise execution of complex movements. Traditional linear biomechanical analyses of wrestling techniques often focus on averaged data points, overlooking motor pattern variability and nonlinear dynamic characteristics. Understanding these nonlinear dynamics can enhance skill acquisition, injury prevention, and training optimization. This study is the first to apply multidimensional recurrence quantification analysis (MDRQA) of electromyography (EMG) signals to compare motor patterns in elite and sub-elite wrestlers during a shadow freestyle tie-up drill (SFTUD).

Methods: This cross-sectional, descriptive-analytical observational study recorded EMG signals from the triceps, biceps, anterior deltoid, and latissimus dorsi of the dominant upper limb during a 15-second SFTUD. Determinism (%DET) and laminarity (%LAM) were used to assess repeatability and stability, while diagonal (EntL) and vertical (EntV) entropy measured complexity and adaptability.

Results: Elite wrestlers exhibited significantly higher %DET and %LAM, indicating greater consistency in their motor patterns. Elevated EntL and EntV values further suggest enhanced complexity and adaptability in neuromuscular control, reflecting the chaotic dynamics associated with superior performance.

Conclusion: These findings underscore the importance of nonlinear motor pattern dynamics in the development of wrestling skill. MDRQA can identify expertise-related movement patterns, enabling coaches and practitioners to design targeted training programs that optimize performance and reduce injury risk.

*Corresponding author: Kazem Esfandiarian-Nasab; Department of Motor Behavior and Sports Biomechanics, Faculty of Sports Sciences, University of Mazandaran, Mazandaran, Iran, **Tel:** +989179413778, **Post Code:** 4751876171, **Email:** kazem.esfandiarian@gmail.com

Introduction

Motor patterns are defined as coordinated movements generated by the neuromuscular system during the execution of a specific action [1]. These patterns evolve as athletes acquire and refine skills, transitioning from high variability in early learning stages to more stable and efficient movements as proficiency increases [1-5]. In wrestling research, conventional biomechanical approaches have been widely used to analyze movement patterns during techniques such as double-leg takedowns [6,7], snap-downs [8], and arm-throw techniques [9,10]. Additionally, video analysis of matches has been employed to assess athletes' technical performance in competitive settings [11-13]. However, these traditional methods are limited in scope: they primarily focus on averaged measures or key movement events and fail to capture the dynamic, adaptive, and complex characteristics of motor patterns that underpin skill development in wrestling [3,14,15].

By incorporating concepts such as variability and attractors, dynamical systems theory provides a framework for the nonlinear analysis of sports movements, allowing researchers to uncover the hidden dynamics underlying athletes' performance [16,17]. A key concept within this framework is **recurrence**, which describes a system's tendency to return to previously established states or motor patterns [1,18]. In wrestling, for example, an athlete may repeatedly employ a particular technique or return to a specific body position, reflecting the neuromuscular system's consolidation of effective motor strategies [4]. Importantly, even with recurrence and stabilization, variability persists during repeated skill execution. This variability is not a flaw; rather, it enables athletes to adapt their movements to the dynamic conditions of a match, enhancing the success of each technique [4,19,20]. Examining these recurrence patterns provides insight into the robustness, complexity, and adaptability of motor patterns, offering a deeper understanding of skill development and performance optimization.

Analyzing wrestlers' recurrent patterns in neuromuscular outputs, such as electromyography (EMG), can provide valuable insights into the neural–muscular coordination underlying skilled movements. Understanding these temporal patterns is particularly important for evaluating wrestling maneuvers, such as the shadow freestyle tie-up drill (SFTUD), which demands precise timing and highly coordinated muscle activation [4]. Recurrence-based analysis of EMG data offers a unique perspective on the complexity and adaptability of neuromuscular control, highlighting how elite wrestlers adjust muscle activity in response to an opponent's unpredictable actions. Identifying distinct recurrent patterns in EMG recordings from elite athletes enables researchers to characterize motor control strategies across skill levels, potentially yielding novel indicators of skill acquisition and informing the development of optimized training protocols to accelerate skill progression.

In recent years, recurrence quantification analysis (RQA) has emerged as a powerful tool for visualizing and quantifying recurrence patterns in complex systems. By utilizing recurrence plots and quantitative indices such as determinism (%DET), laminarity (%LAM), and entropy, RQA enables researchers to investigate key dynamic characteristics of motor patterns, including stability, repeatability, complexity, and adaptability [21,22]. This method has been successfully applied in movement studies across various sports, including slacklining [23], gymnastics [2], dance [24], golf [25], and weightlifting [26]. Additionally, cross-recurrence quantification analysis (CRQA) has been employed to explore motor coordination and interaction patterns in activities such as dance and taekwondo [18,27].

Despite the advantages and widespread use of RQA and CRQA in sports science, their application to tasks requiring the coordination of multiple body segments—such as those encountered in combat sports—remains limited [28,29]. This gap underscores the need for a multidimensional approach to capture the complex, coordinated patterns inherent in such motor skills. Multidimensional recurrence quantification analysis (MDRQA) provides a framework for simultaneously examining recurrent signal behaviors across multiple channels, offering a more comprehensive depiction of motor patterns [21,22,29]. While MDRQA has been effectively applied to study reaching tasks [30,31] and to investigate collaborative actions and social coordination, such as in origami boat production [29]. Its potential to evaluate skill levels and neuromuscular patterns in sports like wrestling has yet to be fully realized.

To address this gap, the present study is the first to employ MDRQA to investigate neuromuscular patterns in elite and sub-elite wrestlers during the execution of the shadow freestyle tie-up drill (SFTUD). We propose two primary hypotheses. First, elite wrestlers are expected to exhibit greater consistency in their motor patterns than sub-elite wrestlers, as reflected in higher %DET and %LAM values. Second, elite wrestlers are expected to demonstrate greater motor complexity and adaptability, as indicated by elevated entropy values associated with determinism and laminarity measures. By testing these hypotheses, this study seeks to deepen our understanding of neuromuscular control in wrestling and to provide insights that may inform skill acquisition, injury prevention, and the optimization of training strategies across different levels of expertise.

Methods

Study Design

This study employed an original descriptive-analytical, cross-sectional observational design to investigate the nonlinear dynamics of neuromuscular patterns in elite and sub-elite wrestlers using multidimensional recurrence quantification analysis (MDRQA).

Participants

A preliminary pilot study, combined with statistical guidelines, was used to determine the appropriate sample size. Using a significance level of 0.05 and a statistical power of 0.8, the calculated effect sizes for laminarity (%LAM) and diagonal entropy (EntL) were 0.77 and 0.98, respectively. Based on a two-tailed independent t-test, the required sample sizes were 28 participants for %LAM and 19 participants for EntL. To ensure consistency across measures and to maximize statistical reliability, 28 participants were enrolled in each of the elite and sub-elite cohorts.

The elite group included wrestlers with at least 5 years of training experience and at least one top-ranking placement in provincial competitions over the past 5 years (mean age: 16.4 ± 1.1 years; height: 1.70 ± 0.12 m; weight: 65 ± 10.8 kg). The sub-elite group comprised wrestlers who did not meet these elite criteria and had only competed at the regional level (mean age: 16.6 ± 0.17 years; height: 1.72 ± 0.10 m; weight: 66.7 ± 10.0 kg).

Eligibility criteria required participants to be free of orthopedic or neuromuscular disorders, recent trauma (within the past six months), illnesses, or any condition that could impair performance of the SFTUD or pose a safety risk. As all participants were under 18 years of age, written informed consent was obtained from their parents. The study protocol was approved by the Ethics Review Board of UMZ University (IR.UMZ.REC.1402.032).

Data Collection

This study analyzed the SFTUD, a solo wrestling exercise designed to improve athletes' grappling skills [32]. During the drill, the wrestler simulates a tie-up or clinch with an imaginary opponent, performing shadow wrestling techniques. The exercise requires controlling the opponent's hands and maintaining a dominant position in a freestyle wrestling tie-up, all without a physical partner (Fig. 1).

Each participant performed the SFTUD for 30 seconds, and a 15-second segment (from 10 to 25 seconds) was selected for analysis. Surface EMG signals were recorded from the triceps, biceps, anterior deltoid, and latissimus dorsi of the dominant upper limb using a Biovision EMG system in combination with DASYLAB software (V 10.00.03) at a sampling rate of 1000 Hz. Before electrode placement, the skin was disinfected with alcohol and shaved if necessary to reduce impedance. Bipolar Ag/AgCl electrodes were positioned 20 mm apart, aligned with the direction of each muscle's fibers, following the methodology described in previous research [32].

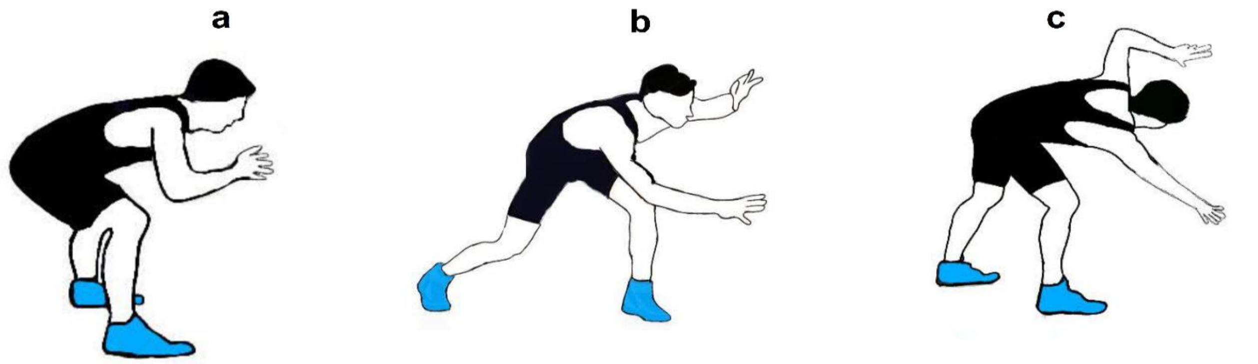

Figure 1: Graphical representation of the shadow freestyle tie-up drill (SFTUD). This drill involves (a) an initial stance with a flexed posture and hands prepared for engagement and (b & c) extending the arms forward to simulate gripping an imaginary opponent, accompanied by footwork and pivoting movements.

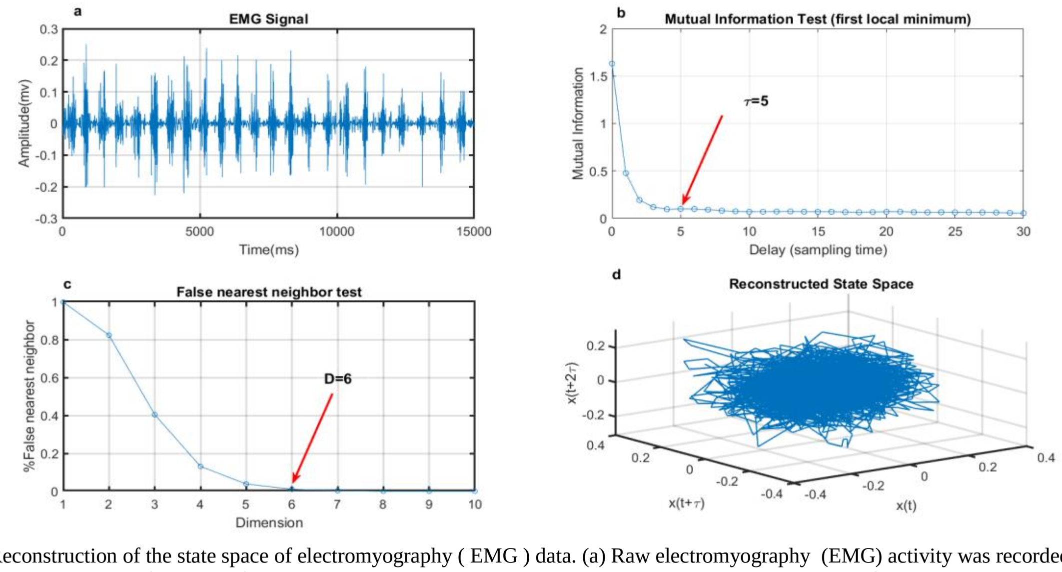

Figure 2: Reconstruction of the state space of electromyography (EMG) data. (a) Raw electromyography (EMG) activity was recorded from the target muscles. (b) Depiction of mutual information evaluation applied to determine the best delay time (τ). (c) The false nearest-neighbor method was applied to determine the embedded dimension (D). (d) Reconstruction of the electromyography (EMG) signal's three-dimensional state space for each muscle.

MDRQA

Raw EMG signals were filtered using a Butterworth bandpass filter (5–500 Hz). The resulting time-domain signals (Fig. 2a) were then embedded into a multidimensional state space to investigate the underlying dynamics and interrelationships among muscle signals (Fig. 2d). For each muscle, a time-delay vector of predetermined dimension was constructed as follows:

1. Time delay (τ): The spacing between successive samples in the time-delay vector was determined using the mutual information method [15]. The optimal delay for each muscle corresponded to the first minimum on the mutual information versus time-delay curve (Fig. 2b).

2. Embedded dimension (D): The dimensionality of the reconstructed state space was estimated using the false nearest-neighbor method [15]. For each muscle, D was chosen so that the percentage of false nearest neighbors was minimized to zero (Fig. 2c).

After establishing the optimal time delay and embedding dimension, the state space of each muscle's EMG data was reconstructed as follows:

$$W_j = \begin{pmatrix} x_{j,1} & x_{j,1+\tau} & x_{j,1+2\tau} & \cdots & x_{j,1+(D-1)\tau} \\ x_{j,2} & x_{j,2+\tau} & x_{j,2+2\tau} & \cdots & x_{j,2+(D-1)\tau} \\ x_{j,3} & x_{j,3+\tau} & x_{j,3+2\tau} & \cdots & x_{j,3+(D-1)\tau} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{j,N-(D-1)\tau} & x_{j,N-(D-2)\tau} & x_{j,N-(D-3)\tau} & \cdots & x_{j,i} \end{pmatrix} i = N-(D-1)\tau, j = 1:4 \quad (1)$$

In this context, **N** denotes the total number of EMG data points for each muscle, and j denotes the index for the four recorded muscles. After reconstructing the state-space trajectory for each muscle, the resulting vectors were concatenated to form a single multidimensional signal:

$$W = [W_1, W_2, W_3, W_4] \quad (2)$$

This integrated signal captures the coordinated muscular activation and the fundamental dynamic patterns expressed during the SFTUD task.

A multidimensional recurrence plot (MRP) was then constructed based on the Euclidean distance matrix computed among all points in the reconstructed multidimensional state space [21,22]. This matrix quantifies the degree of similarity or dissimilarity in neuromuscular activation across time:

$$R_{i,j} = \theta(\varepsilon - \|W_i - W_j\|) \qquad i,j = 1,2,\dots,n \quad (3)$$

Here, $\| W_i - W_j \|$denotes the Euclidean distance between two state-space vectors, and εserves as an adaptive threshold defining recurrence neighborhoods. In accordance with previous MDRQA research, $\varepsilon$was set to 10% of the maximum distance within the matrix [30]. The Heaviside function θconverts distances into binary values (0 or 1) to indicate the absence or presence of recurrence. In the resulting recurrence plot, distances below the threshold (recurrences) appear as black points, whereas non-recurrences appear as white points.

Recurrence metrics were subsequently computed according to the procedures described in[4], including:

%DET: the percentage of recurrent points forming diagonal line structures relative to the total number of recurrent points. This metric reflects the *predictability* and *regularity* of the system's dynamic behavior.

%LAM: the percentage of recurrent points that form vertical line structures relative to the total number of recurrent points. This metric reflects the presence of laminar states or periods during which the system exhibits minimal change.

EntL: the Shannon entropy of diagonal lines and quantifies the distributional richness of their lengths. Higher entropy values indicate greater variability in deterministic sequences and thus capture the temporal complexity embedded in recurrence patterns.

EntV: the Shannon entropy of vertical lines and measures the variability in laminar phases. This metric characterizes the degree of temporal fluctuation within periods of reduced system dynamics, thereby providing insight into the stability or intermittency of the underlying musculoskeletal coordination.

Statistical Analysis

Before all analyses, the distribution of each variable was assessed using the Shapiro–Wilk test to evaluate normality. Group differences in MDRQA-derived metrics between elite and sub-elite athletes were examined using independent samples t-tests. All MDRQA computations were performed in MATLAB (version 2023a), and statistical analyses were conducted using GraphPad Prism (version 10). The required sample size was estimated using G*Power (version 3.1.9.2). Statistical significance was defined as $P < 0.05$.

Results

The findings show elite wrestlers had significantly higher %DET values (90.50 ± 9.4 vs. 79.2 ± 16.19, P = 0.002), %LAM values (94.4 ± 6.2 vs. 85.5 ± 14.2, P = 0.006), EntL (3.17 ± 0.62 vs. 2.59 ± 0.59, P < 0.001), and EntV (3.75 ± 0.79 vs. 2.91 ± 0.972, P = 0.002) during the SFTUD maneuver compared with the sub-elite group (Fig. 3).

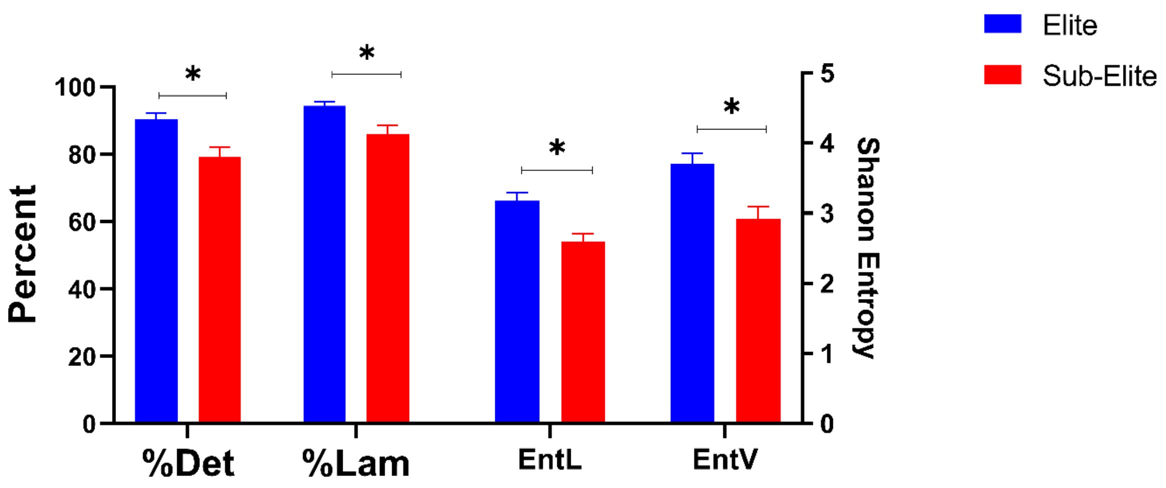

Figure 3: Comparison of recurrence patterns in elite versus sub-elite wrestlers performing the shadow freestyle tie-up drill (SFTUD). Determinism (%DET) and Laminarity (%LAM) are displayed on the left axis, whereas Shannon entropy values for horizontal (EntL) and vertical (EntV) recurrence are shown on the right axis. Asterisks (*) above the bars denote statistically significant differences between the groups (P < 0.05).

Discussion

The present study revealed distinct neuromuscular coordination patterns between elite and sub-elite wrestlers, as quantified by MDRQA of EMG signals. Elite wrestlers demonstrated higher levels of predictability, stability, and neuromuscular adaptability, as reflected by increased %DET, %LAM, EntL, and EntV values. These metrics collectively indicate more structured yet flexible motor control strategies, consistent with advanced skill acquisition and expert performance. The observed differences align with our hypotheses and provide evidence that elite athletes possess more refined and efficient motor patterns, which likely support superior task execution under dynamic and demanding conditions.

Repeatability and Stability of Motor Patterns

Elite wrestlers demonstrated a higher %DET, reflecting greater predictability in their motor patterns. Such predictability likely arises from consistent neuromuscular activation developed through years of specialized, high-volume training and accumulated competitive experience. This observation aligns with motor learning theories, suggesting that increasing expertise is accompanied by reduced performance variability and more stable execution of movement patterns [33,34]. In line with this framework, elite wrestlers in the present study exhibited more repeatable and structured muscle activation during the SFTUD. Moreover, their elevated %LAM values indicate an enhanced capacity to sustain stable neuromuscular states over time. This ability is critical in wrestling, where maintaining balance, control, and optimal posture against continuously changing external forces is essential for successful performance.

Viewed through the lens of nonlinear dynamics, elite wrestlers demonstrate increased repeatability and stability, suggesting that their motor systems function within a more stable attractor state [2]. Reduced chaotic fluctuations characterize such attractor states [2], enhanced motor control [35], and greater resilience to perturbations [36]. In contrast, sub-elite wrestlers exhibited lower %DET and %LAM values, reflecting higher variability and reduced stability in their neuromuscular patterns. This variability is indicative of an exploratory phase of motor learning in which efficient motor solutions have not yet been fully established. This pattern aligns with Bernstein's motor learning framework, which proposes that novices initially "freeze" degrees of freedom to simplify movement control and gradually "free" them as skill and coordination improve [37]. Accordingly, sub-elite wrestlers appear to be in this intermediate developmental stage, actively refining their motor strategies but lacking the stability and consistency observed in elite performers.

Therefore, training programs should aim to enhance the stability and repeatability of motor patterns, as these qualities directly influence technical effectiveness. Prior research has demonstrated that highly skilled wrestlers achieve technique-effectiveness rates exceeding 70%, whereas less-skilled counterparts reach only about 25% [11-13]. This substantial disparity underscores the critical role of stable, consistent neuromuscular patterns in successful performance. To address this, coaches should prioritize drills that develop neuromuscular control and proprioception during the initial stages of learning the SFTUD. Such training may include balance- and posture-oriented exercises, as well as tasks incorporating variable resistance or instability. These approaches foster more stable muscle activation patterns, enhance technical execution, and reduce the risk of injury.

This study's application of MDRQA provides a novel means of quantifying the interplay of muscle activations during dynamic wrestling maneuvers, offering coaches and rehabilitation specialists an objective and sensitive measure of motor control. Such metrics can help identify specific weaknesses or instabilities in neuromuscular coordination, thereby enabling targeted training interventions designed to optimize motor patterns and enhance overall performance.

Motor Pattern Complexity and Adaptive Capacity

Elite wrestlers demonstrated elevated EntL values, reflecting a broader repertoire of neuromuscular control strategies. This suggests a capacity to execute more intricate motor patterns and to employ diverse tactical solutions flexibly. Their higher EntV values further indicate enhanced adaptability, enabling fine-tuned modulation of motor pattern duration in response to evolving movement demands.

These findings imply that elite wrestlers operate near the "edge of chaos," a region in which motor behavior balances stability and flexibility [38,39]. Functioning in this zone allows athletes to adapt effectively to competitive demands by leveraging the dynamic properties of complex adaptive systems. In doing so, they can navigate among multiple attractor states—some exhibiting fractal or chaotic characteristics—and transition rapidly between stable coordination patterns as required.

This capacity is critical in wrestling, where athletes must respond to opponents' actions in real time while maintaining both control and precision. In contrast, sub-elite wrestlers exhibited lower entropy values, indicating a reliance on a narrower set of neuromuscular strategies and, consequently, reduced complexity and adaptability. Such limitations suggest that their motor systems are less capable of adjusting to wrestling's dynamic and unpredictable demands. This reduced adaptability is consistent with the early stages of motor learning, during which athletes tend to rely on simplified and less flexible coordination patterns.

These findings highlight the importance of designing training programs that promote exploration of diverse movement repertoires and the development of adaptive strategies. Incorporating drills that simulate unpredictable opponent actions and demand rapid decision-making can foster more complex neuromuscular patterns, enhancing athletes' ability to respond effectively under dynamic competitive conditions. Moreover, applying MDRQA to quantify motor pattern complexity and adaptability provides a valuable tool for coaches and clinicians. By monitoring these metrics, practitioners can gain insights into athletes' neuromuscular control strategies and tailor interventions to optimize performance while minimizing injury risk in unpredictable sporting environments.

Comparison with Past Studies

Our findings align with prior research linking expertise to movement repeatability, suggesting that elite athletes exhibit greater predictability in their motor patterns. Similar patterns have been observed in slackliners [23], gymnasts [2], and weightlifters [26], where highly skilled performers consistently displayed more stable, repeatable movements than less-skilled individuals or control groups. These studies collectively indicate that mastery of motor skills enhances both movement consistency and accuracy. Nevertheless, traditional RQA and CRQA approaches provide only partial insights into motor control, as they generally limit analysis to a few kinematic or kinetic variables, failing to capture the full complexity of coordinated neuromuscular patterns.

The MDRQA approach employed in this study provides a comprehensive perspective on coordinated motor control, enabling the identification of specific neuromuscular patterns associated with expertise. These insights can inform the design of tailored training programs aimed at enhancing performance across skill levels by facilitating the development of refined motor patterns in sub-elite athletes.

However, some studies have reported lower %DET values in elite dancers [24,27] and taekwondo athletes [18] compared with their less-skilled counterparts. This discrepancy likely reflects the unique demands of each sport. For instance, the taekwondo tasks involved simple forward and backward movements, which may require less complex control than the multi-muscle, dynamic coordination inherent in wrestling. Similarly, single-leg standing analyses in dance may pose minimal challenge for professional dancers. In contrast, our study assessed athletes performing the SFTUD under conditions closely simulating competitive wrestling. Moreover, methodological differences—such as the use of principal component analysis before calculating recurrence indices [18], may affect results, as such preprocessing can disrupt the temporal structure of the data and thereby influence recurrence measures.

Coaches and trainers can leverage these findings to design training programs that incorporate exercises and drills promoting both diverse and adaptable movement patterns, thereby enhancing athletes' responsiveness to the dynamic demands of competition. Future research could extend the application of MDRQA to other sports to examine the relationships between movement complexity, adaptability, and performance. Such investigations may foster interdisciplinary collaboration among sports scientists, coaches, and rehabilitation specialists, ultimately contributing to the optimization of training regimens and rehabilitation protocols.

This study has several limitations. First, its cross-sectional observational design precludes causal inferences, and results should be interpreted accordingly. Second, EMG data were collected from a limited set of muscles during a single drill, which may not fully capture the complexity of real match conditions. Third, the sample consisted of adolescent wrestlers, potentially limiting the generalizability of the findings. Future research should include larger, more diverse cohorts and examine multiple techniques to validate and extend these results.

Conclusion

This study demonstrated that elite wrestlers exhibit neuromuscular activation patterns that are more predictable, stable, complex, and adaptable than those of sub-elite wrestlers during SFTUD performance. These findings underscore the critical role of advanced motor control in athletic success and highlight the potential of MDRQA as a tool for analyzing and optimizing motor patterns in sports. Integrating these insights into training and rehabilitation programs can help coaches and practitioners enhance performance and support the development of elite athletes. Additionally, rehabilitation specialists can design targeted interventions to improve motor control and neuromuscular strategies in athletes recovering from injuries, facilitating a safe and effective return to competition. Overall, a deeper understanding of neuromuscular control mechanisms in wrestling can inform more effective training and rehabilitation approaches, ultimately improving performance and reducing injury risk.

Author Contributions

Kazem Esfandiarian-Nasab contributed to the study's conception and design, data analysis and interpretation, and drafting and revising the manuscript for intellectual content. Mansour Eslami assisted in drafting and provided critical feedback on the manuscript. Fateme Salari-Esker and Rohollah Yousefpour gave final approval for publication. All authors reviewed and endorsed the final version of the manuscript.

Acknowledgements

The authors declare that there are no additional individuals or organizations to acknowledge.

Funding Source

This study received no external funding.

Notes on Figures

All figures were produced by the authors, and no permissions are required.

Conflict of Interest: The authors report no conflicts of interest..

References

1. Kelso J. Dynamic patterns: the self-organization of brain and behavior. MIT Press; 1995.
2. Harrison SJ, Stergiou N. Complex adaptive behavior and dexterous action. Nonlinear Dynamics Psychol Life Sci. 2015;19(4):345–94.
3. Burton S, Vicinanza D, Exell T, Newell KM, Irwin G, Williams GKR. Attractor dynamics of elite performance: the high bar long swing. Sports Biomech. 2021;23(10):1384–97.
4. van Emmerik REA, Ducharme SW, Amado AC, Hamill J. Comparing dynamical systems concepts and techniques for biomechanical analysis. J Sport Health Sci. 2016;5(1):3–13.
5. Esfandiarian-Nasab K, Eslami M, Salari-Esker F, Yousefpour R. Unraveling chaotic motor patterns of elite and sub-elite wrestlers in snap-down technique using multidimensional recurrence quantification analysis of muscle activity. Comput Biol Med. 2025;196:110673.
6. Beinabaji H, Eslami M, Hosseininejad SE, Esmaili Paeen Afrakoti I. Muscle synergy during double-leg attack maneuver: a comparison between elite and sub-elite wrestlers. J Adv Sport Technol. 2023;7(4):11–24.
7. Yamashita D, Arakawa H, Wada T, Yumoto K, Fujiyama K, Nagami T, et al. Whole-body mechanics of double-leg attack in elite and non-elite male freestyle wrestlers. Front Sports Act Living. 2020;2(June):58.
8. DeCastro N, Wu T, editors. The examination of upper limb ambidexterity in wrestling snap down technique. ISBS-Conference Proceedings Archive; 2015.
9. Stordopoulos D, Giannakou E, Manaveli P, Barbas I, Gourgoulis V, Aggeloussis N. Reliability of lower limb kinematics during the arm-throw wrestling technique. Int J Wrestl Sci. 2016;6(2):67–73.
10. Barbas I, Aggeloussis N, Podlivaev B, Shakhmuradov Y, Mirzaei B, Tunnemann H. Biomechanical protocol to assist the training of arm-throw wrestling technique. Int J Wrestl Sci. 2014;2(2):93–103.
11. Fujiyama K, Yamashita D, Nishiguchi S, Ito M. Technical-tactical analysis of men's wrestling: a case study of the 72nd National Athletic Meet of 2017 in Japan. Int J Wrestl Sci. 2019;9:1–6.
12. Kajmovic H, Kapur A, Radjo I, Mekic A. Differences in performance between winners and defeated wrestlers in the European Championships for cadets. Int J Perform Anal Sport. 2014;14(1):252–61.
13. Kajmović H, Kapur A, Huremović D, Kapo S, Colakhodzic E. Differences in performance indicators between winners and defeated female cadet wrestlers. J Eurasia Sport Sci Med. 2019;1(1):10–23.
14. Glazier PS, Mehdizadeh S. In search of sports biomechanics' holy grail: can athlete-specific optimum sports techniques be identified? J Biomech. 2019;94:1–4.
15. Stergiou N. Nonlinear analysis for human movement variability: CRC Press; 2018.
16. Torrents C, Balagué N. Dynamic systems theory and sports training. Balt J Sport Health Sci. 2006;1(60).
17. Favela LH. Dynamical systems theory in cognitive science and neuroscience. Philos Compass. 2020;15(8):e12695.
18. Straiotto B, Marwan N, James D, Seeley P. Recurrence analysis discriminates martial art movement patterns. Eur Phys J Spec Top. 2023;232(1):151–9.
19. Preatoni E, Hamill J, Harrison AJ, Hayes K, Van Emmerik RE, Wilson C, et al. Movement variability and skills monitoring in sports. Sports Biomech. 2013;12(2):69–92.
20. Ranganathan R, Lee M-H, Newell KM. Repetition without repetition: Challenges in understanding behavioral flexibility in motor skill. Front Psychol. 2020;11:2018.
21. Marwan N, Romano MC, Thiel M, Kurths J. Recurrence plots for the analysis of complex systems. Phys Rep. 2007;438(5-6):237–329.
22. Webber Jr CL, Zbilut JP. Recurrence quantification analysis of nonlinear dynamical systems. Tutorials in contemporary nonlinear methods for the behavioral sciences. 2005;94(2005):26–94.
23. Kodama K, Yamagiwa H, Yasuda K. Bimanual coordination in a whole-body dynamic balance sport, slacklining: a comparison of novice and expert. Motor control. 2021;25(3):462–74.
24. Schmit JM, Regis DI, Riley MA. Dynamic patterns of postural sway in ballet dancers and track athletes. Exp Brain Res. 2005;163(3):370–8.
25. Stockl M, Lamb PF. The variable and chaotic nature of professional golf performance. J Sports Sci. 2018;36(9):978–84.
26. Felici F, Rosponi A, Sbriccoli P, Filligoi GC, Fattorini L, Marchetti M. Linear and non-linear analysis of surface electromyograms in weightlifters. Eur J Appl Physiol. 2001;84(4):337–42.
27. Kiefer AW, Riley MA, Shockley K, Sitton CA, Hewett TE, Cummins-Sebree S, et al. Multi-segmental postural coordination in professional ballet dancers. Gait Posture. 2011;34(1):76–80.
28. Wallot S. Multidimensional cross-recurrence quantification analysis (MdCRQA) - a method for quantifying correlation between multivariate time-series. Multivariate Behav Res. 2019;54(2):173–91.
29. Wallot S, Roepstorff A, Monster D. Multidimensional recurrence quantification analysis (MdRQA) for the analysis of multidimensional time-series: a software implementation in MATLAB and its application to group-level data in joint action. Front Psychol. 2016;7(NOV):1835.
30. Li J, Wei N, Yue S, Li K, editors. Multidimensional recurrence quantification analysis of multi-muscle synergy in elderly during standing on slopes. 2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC); 2020: IEEE.
31. Zhao K, Wen H, Guo Y, Scano A, Zhang Z. Feasibility of recurrence quantification analysis (RQA) in quantifying dynamical coordination among muscles. Biomed Signal Process Control. 2023;79:104042.
32. Criswell E. Cram's introduction to surface electromyography. Jones & Bartlett Learning. 2010.
33. Latash ML. Fundamentals of motor control: Academic Press; 2012.
34. Marineau E, Ducas J, Mathieu J, Rodriguez ADP, Descarreaux M, Abboud J. From novice to expert: how expertise shapes motor variability in sports biomechanics—a scoping review. Scand J Med Sci Sports. 2024;34(8):e14706.
35. Komar J, Seifert L, Thouvarecq R. What variability tells us about motor expertise: measurements and perspectives from a complex system approach. Mov Sport Sci Sci Motricité. 2015;89(3):65–77.
36. Cignetti F, Schena F, Rouard A. Effects of fatigue on inter-cycle variability in cross-country skiing. J Biomech. 2009;42(10):1452–9.
37. Bernstein N. The co-ordination and regulation of movements. Pergamon Press; 1967.
38. Stergiou N, Decker LM. Human movement variability, nonlinear dynamics, and pathology: is there a connection? Hum Mov Sci. 2011;30(5):869–88.
39. Esfandiarian-Nasab K, Eslami M, Salari-Esker F, Yousefpour R. Skill Differentiation in Wrestling: Relationship Between Muscle Complexity and Local Dynamic Stability in Neuromuscular Control. J Mot Behav. 2025(1940-1027):1–16.