The Biomechanical Construction of Kinetic Chain Synergy in Competitive Recurve Archery

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Abstract: *In competitive recurve archery, athletes must accumulate and instantaneously release energy under conditions that demand high stability and precision, forming a complex kinetic chain synergy system. Based on sports biomechanics and neural control theory, this study systematically analyzes the kinetic chain structure involved in archery movements, identifies the multi-level synergistic relationships among the shoulder–elbow–wrist force chain, the trunk stabilization chain, and the lower limb support chain, and explores the mechanical coupling characteristics at key nodes. On this basis, a multi-scale modeling framework incorporating temporal regulation, energy transmission, and synergy efficiency is constructed to reveal the mechanistic impact of synergy efficiency on archery performance and to clarify the mechanical bottlenecks that limit movement accuracy. Furthermore, the study proposes strategies for kinetic chain reconstruction and optimization, and establishes a performance consistency evaluation system, providing theoretical support and modeling tools for technical analysis and training interventions.*

Keywords: *recurve archery; kinetic chain; synergy mechanism; biomechanics; system modeling; structural optimization*

Introduction

In competitive archery—particularly in recurve events—athletes are required to precisely regulate posture, force control, and timing under high-tension conditions, constituting a typical process of kinetic chain coordination. Existing studies on archery movements have primarily focused on technical element analysis and training methods, with limited research from the perspective of system dynamics to model and analyze the underlying mechanisms of movement structure. The movement characteristics of recurve archery indicate that kinetic output is not the result of isolated muscle groups, but rather depends on spatial and temporal energy coupling and coordinated mobilization across multiple joints throughout the body. Therefore, constructing a biomechanical mechanism model centered on the kinetic chain is essential for identifying performance bottlenecks, optimizing force generation structures, and enhancing overall system output efficiency. This study, grounded in multi-scale synergy mechanism theory, integrates musculoskeletal modeling with data-driven analysis methods to explore in depth the structure and operational mechanisms of the kinetic chain in recurve archery and proposes targeted optimization pathways, aiming to provide theoretical support and quantitative tools for technical refinement and training intervention.

1. Analysis of the Kinetic Chain System in Recurve Archery

1.1 Definition of the Applicability of the Kinetic Chain Concept in the Motor System

The kinetic chain, as an integrative concept in biomechanics, originates from the intersection of sports biomechanics and neural control theory. It aims to elucidate the mechanisms of energy generation, transmission, and integration across multi-joint structures during complex movements. This theory posits that motor output is not produced by the isolated action of a single joint or muscle group but rather emerges from the synergistic interaction of multiple biomechanical units. These include skeletal lever systems, muscle recruitment sequences, joint-driven coupling, and dynamic regulation of timing and tension by the central nervous system. The stability and integrity of the kinetic chain system directly influence spatial accuracy, energy efficiency, and resistance to disturbances during movement, thereby holding core theoretical value in technical modeling, motion mechanism analysis, and performance prediction in specialized sports [1].

In competitive recurve archery, athletes must coordinate multiple body segments efficiently during the alternating phases of static tension and dynamic release. These movement characteristics closely align with the operational features of a multi-level kinetic chain system. The draw and release actions depend not only on the explosive force of the upper limb muscles but also on the lower limbs for stable support, the trunk for axial stabilization, and the multilevel structure for transmitting ground reaction forces to the distal end, achieving a unified effect of kinetic energy convergence and posture control. The introduction of kinetic chain theory redefines recurve archery not as a mere act of technical imitation but as a high-level movement construction model grounded in system dynamics. Functional analysis of the kinetic chain structure enables the precise identification of key synergy nodes that constrain movement efficiency, providing a theoretical foundation and pathway orientation for technical optimization, movement restructuring, and training intervention.

1.2 Identification of Major Kinetic Chain Pathways in Recurve Archery Motion Structure

The execution of competitive recurve archery movements displays distinct structural phases, including initial stance, drawing, static aiming, string release, and follow-through adjustment. Throughout these steps, the kinetic chain must remain continuous, stable, and highly synchronized. The spatial structure of the kinetic chain comprises three primary synergistic systems: the upper limb kinetic chain, the trunk stabilization chain, and the lower limb support chain. The upper limb chain, consisting of the scapula, humerus, radius and ulna, and wrist-hand joints and muscles, serves as the core channel for terminal energy release and is responsible for precision in directional control and force output. This pathway relies on coordinated joint angles at the shoulder, elbow, and wrist, tension regulation via isometric muscle contractions, and dynamic compensation for reactive force disturbances, forming a complex yet highly integrated energy release structure.

Simultaneously, the trunk stabilization chain, functioning as a bridge between upper and lower limbs, must maintain axial rigidity and tension balance through core musculature, providing a stable base and ensuring axial force transmission throughout the movement. The lower limb support chain begins at the ground and establishes a centripetal force transmission path through the hip, knee, and ankle joints. It not only facilitates the initial convergence of ground reaction force but also assists in posture stabilization via micro-adjustments of small muscle groups. These three kinetic systems form a functionally closed loop in a bottom-up sequence, achieving efficient coordination in both temporal and spatial dimensions. Identifying the functional boundaries and collaborative relationships among these pathways aids in constructing biomechanical models of movement execution, thereby offering an operational structural basis for kinetic chain intervention and optimization [2].

1.3 Analysis of the Mechanical Coupling Characteristics Between Kinetic Chain Nodes

The synergistic functioning of kinetic chain nodes fundamentally depends on their coupling strength and mechanical transmission efficiency. Mechanical coupling refers to the interdependent relationships between adjacent nodes in terms of angular velocity, tension, torque, and other variables. This coupling is influenced not only by anatomical structure but also by the central nervous system’s precise regulation of activation sequences and timing windows across motor units. In recurve archery, the shoulder–elbow–wrist chain achieves high-precision force transmission through continuous angular momentum transfer and synchronized adjustment of joint stiffness. Any deviation in activation timing or disruption in tension maintenance at any node can interrupt energy transmission, resulting in systemic disturbances that impair aiming accuracy and stability.

From a systems dynamics modeling perspective, inter-nodal coupling relationships can be quantitatively described using multidimensional nonlinear functions. Common indicators include torque synchronization index, joint coordination phase difference, and muscle recruitment complementarity. For example, during the drawing phase, the regulation of core muscle tension is closely related to shoulder joint stability. Inadequate core control often leads to instability in the draw path, which may trigger compensatory movements in the upper limbs and compromise the stability of the aiming line. Likewise, insufficient activation of the lower limb support chain can weaken the upward transmission of ground reaction forces within the kinetic chain, increasing fluctuations in the system’s center of gravity. Therefore, precise quantitative analysis of coupling mechanisms not only reveals potential risk points within the internal operation of the system but also provides a structured evaluation framework for high-level movement coordination modeling and the optimization of individual movement characteristics.

2. Modeling the Kinetic Chain Synergy Mechanism in Recurve Archery

2.1 Multiscale Construction Logic of the Synergy Mechanism

The construction of the synergy mechanism in recurve archery should not be limited to linear analysis within a single dimension of movement, but should instead be based on the coordination of structures and functions across multiple scales. The multiscale kinetic chain system relies on the synergistic coupling among: micro-level muscle recruitment and neural excitation patterns; meso-level joint coupling and torque distribution; and macro-level postural control and energy output—all of which collectively support overall motor performance. At the micro level, the sequential activation of different muscle fiber types directly influences both instantaneous force generation and movement sustainability; at the meso level, inter-joint drive rhythms, angular momentum integration, and force transmission pathways constitute the dynamic core of movement; at the macro level, a whole-body balance system ensures active disturbance control and precision maintenance. It is through this hierarchical and progressive mechanism that the motor system achieves an efficient transition from localized control to global output.

In recurve archery, the quality of movement execution often depends on the synergy across all scales throughout the entire process from drawing to string release. Elite athletes are able to achieve synchronous core muscle activation, dynamic joint angle adaptation, and precise control of terminal actions within a very short time span. This level of efficiency is underpinned by the nervous system's capacity for multichannel regulation and feedback control of signals across different scales. To better understand this systemic mechanism, a hierarchical dynamic modeling system should be established to simulate response pathways and the coordinated evolution of variables at different scales, and multichannel physiological data modeling methods should be introduced to build a full-chain mechanism from structural analysis to behavioral prediction [3].

2.2 Integrated Mechanism of Temporal Regulation and Mechanical Transmission

In recurve archery, temporal regulation determines not only movement rhythm and coherence, but also directly impacts the stability and precision of the kinetic chain system. The activation timing and duration of different motor units must be tightly synchronized to ensure continuity and directionality of energy transmission. Any temporal deviation at a node—such as early or delayed muscle activation—can result in phase misalignment and disruption in kinetic energy transfer. System operation must satisfy two key constraints: the "activation time window" and the "adjacent node coupling delay," ensuring that each structural unit engages in the movement at its optimal moment and collectively forms the shortest time-delay chain from lower-limb support and trunk stabilization to upper-limb release. For a precision-dependent sport like archery, such timing control is particularly critical.

At the same time, the mechanical transmission mechanism must integrate the flow path of force, directionality of energy, and structural stability. Energy originates from the ground, converges through the lower-limb joint chain, passes through the trunk's central axis, and is ultimately released via the shoulder–elbow–wrist chain. During this process, each node's joint stiffness, angular velocity, and torque output must align with the energy input characteristics of the preceding structure, thereby forming a continuous energy flow. Any transmission blockage or coupling imbalance at a node may not only reduce overall output efficiency but also trigger compensatory movements in local structures, disrupting postural stability. The modeling process should combine multibody dynamics simulation, finite element analysis, and neuromuscular feedback modeling to construct a cross-level, cross-system integrated control model that reveals the complete mechanical signal transmission mechanism in archery movements.

2.3 Mechanistic Influence of Synergy Efficiency on Archery Performance

Synergy efficiency, as a critical parameter for evaluating the operational quality of the kinetic chain system, is reflected in optimal resource allocation among structural units, minimal energy transmission loss, and high repeatability of movement execution. A highly efficient kinetic chain system achieves maximal output with minimal muscle recruitment and demonstrates strong resistance and compensation capabilities against external disturbances. In recurve archery, where precise control is essential, higher synergy efficiency corresponds to greater movement economy, stability, and consistency. Conversely, the presence of redundant activation, force vector misalignment, or torque asymmetry within the system can lead to posture deviation, force errors, and aim-line disturbances, all of which directly affect target accuracy.

To analyze synergy efficiency from a mechanistic perspective, a comprehensive evaluation system integrating mechanical parameters, neural control signals, and movement trajectories should be developed. Key indicators within the evaluation model may include: Energy Concentration Index (ECI), Movement Output Consistency Coefficient (MOCC), and Muscle Activation Redundancy Rate (MARR). These metrics capture energy transmission performance and coupling states across different movement phases. Combined with individual-specific modeling, the system can further identify synergy strengths and risk points in an athlete's technical profile. This evaluation framework not only offers strong explanatory and predictive power, but also supports training feedback, movement correction, and technical fine-tuning—providing data-driven guidance and modeling tools for precision training and structured instruction in high-level competitive archery [4].

3. Biomechanical Optimization Pathways for Kinetic Chain Synergy in Recurve Archery

3.1 Identification of Key Mechanical Bottlenecks in the Synergy Mechanism

In multi-node kinetic chain systems, overall synergy performance is often constrained by regions where coupling strength is insufficient or functional alignment is imbalanced—commonly referred to as mechanical bottlenecks. In competitive recurve archery, such bottlenecks primarily occur in: disrupted force transmission between the shoulder and elbow joints, delayed angular momentum transfer, and weakened trunk control due to untimely activation of core muscle groups. These localized impairments significantly reduce internal energy convergence efficiency, manifesting as directional deviations in force output, postural instability, and reduced aiming accuracy—ultimately compromising output consistency and terminal control precision. The presence of bottleneck nodes not only disrupts the fluidity of the kinetic chain but may also trigger non-physiological compensatory movement patterns, increasing the risk of local fatigue or injury.

Accurate identification of these mechanical bottlenecks requires multimodal acquisition and integrated analysis of high-dimensional movement data. By combining 3D motion capture systems, surface electromyography (sEMG), and ground reaction force platforms, it is possible to synchronously monitor dynamic parameter shifts at key nodes, muscle activation sequences, and energy transmission continuity. For instance, delayed activation of core muscles may produce abnormally high-frequency oscillation signals in the lower back, indicating delayed engagement of the stabilization chain; similarly, asynchronous joint angle changes or uneven torque output between the shoulder and elbow may lead to nonlinear disturbances in terminal force output. Through cross-parameter analysis and synergy index calculations, structural diagnostics of bottleneck regions can be achieved, providing reliable structural foundations and regulatory targets for subsequent kinetic chain reconstruction [5].

3.2 Optimization-Oriented Kinetic Chain Reconstruction Strategies

Kinetic chain reconstruction goes beyond localized force adjustment and constitutes a systemic structural optimization rooted in the logic of synergy. Once key bottleneck regions and their dynamic imbalances are identified, targeted strategies involving adjustments to force sequencing, joint angle corrections, and posture guidance can be devised. For example, if torque dissipation occurs along the shoulder–elbow transmission pathway, reconstruction may involve improving scapular stability and regulating humeral external rotation to optimize energy convergence. If delayed core control leads to trunk displacement, induced training may be used to activate the oblique abdominals and deep lumbar muscles, establishing a stable mechanical anchor during the initial draw. In addition, the release path must also be incorporated into the reconstruction framework by restricting premature wrist engagement, thereby preventing early energy leakage and enhancing both terminal force output and directional consistency.

In practice, kinetic chain reconstruction should follow an integrated "structure–function–behavior" modeling logic. At the micro level, optimization can be guided by EMG-based temporal calibration mechanisms to develop individualized muscle activation maps that serve as consistency baselines in training. At the meso level, 3D motion simulation can be used to construct a “shortest energy pathway” model for real-time monitoring and structural intervention of energy transmission efficiency. At the macro level, attention must be paid to the dynamic evolution of global posture rigidity and center-of-mass stability, ensuring that local adjustments do not compromise systemic balance. Additionally, adaptive training mechanisms based on variable-parameter feedback can be introduced, with synergy efficiency set as a dynamic control variable to enable continuous fine-tuning during training. The essence of kinetic chain reconstruction is a shift from “passive compensation” to “proactive coordination,” achieving a transformation from mechanical path repair to systemic operational redesign—ultimately forming a structurally coherent, dynamically adaptive, and output-stable high-performance movement system.

3.3 Construction of Biomechanical Consistency Evaluation Indicators for Movement Performance

The effectiveness of kinetic chain synergy optimization must be validated and fed back through a visualized, quantifiable indicator system. Biomechanical consistency, as a core variable for assessing the quality of kinetic chain performance, includes intra-system rhythm uniformity of force generation, output directional stability, and synergy in disturbance resistance. In competitive archery, elite athletes exhibit a high degree of temporal alignment and trajectory consistency, with terminal force outputs remaining nearly identical across successive releases. To evaluate this performance, a multidimensional system of metrics should be developed, including time alignment rate, torque output coefficient of variation, and angular momentum fluctuation amplitude, benchmarked dynamically against standard movement models [6].

The development of this indicator system must be grounded in integrated analysis of high-dimensional movement data, incorporating frequency domain energy spectral analysis, trajectory clustering, and synergy measurement models to capture variations in coordination efficiency and structural stability across training phases and individuals. For example, by performing spatiotemporal registration on key-node trajectories recorded over multiple training cycles, deviation ranges and central offset trends can be quantified to determine whether movements fall within a biomechanically consistent performance zone. Additionally, individualized standard motion maps can be constructed and compared against “optimal movement templates” to quantify deviations and generate feedback. This evaluation model not only supports routine training monitoring and technical refinement but also enables early detection of fatigue and performance degradation, thereby advancing recurve archery training toward high-precision, data-driven, and intelligent feedback systems.

Conclusion

This study systematically constructs a biomechanical analysis framework for the synergy mechanism of the kinetic chain in competitive recurve archery, encompassing structural identification, synergy modeling, and optimization implementation. The research clarifies the pathway composition and node distribution of the kinetic chain in recurve archery, reveals the nonlinear coupling relationships and temporal control features between nodes, and proposes multiscale modeling strategies and systematic optimization approaches. Through a mechanistic exploration of synergy efficiency and the identification of mechanical bottlenecks, the study further introduces movement reconstruction strategies and a consistency evaluation system, providing theoretical support and assessment criteria for improving the precision and repeatability of archery techniques. Future research may further explore individualized modeling, AI-based movement analysis systems, and real-time feedback mechanisms to establish a data-driven adaptive training optimization platform, promoting the advancement of recurve archery techniques toward higher precision control and intelligent responsiveness.

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