

A Study on the Effects of Specialized Swimming Training on Muscular Fitness and Explosive Power in College Students

Haijin Pan*

Hainan Vocational University of Science and Technology, Haikou, 571126, China

*Corresponding author: haimian5851@163.com

Abstract: As a whole-body exercise conducted in an aquatic medium, swimming exerts profound influences on muscular function through its unique biomechanical and physiological characteristics. This study aims to systematically elucidate the underlying mechanisms and optimized pathways by which specialized swimming training affects muscular fitness and explosive power in college students. The research first analyzes the biomechanical mechanisms of swimming, its mixed energy metabolism characteristics, and the non-linear resistance loading imposed by the aquatic environment, thereby clarifying the scientific basis for the periodized regulation of training loads. Subsequently, it delves into the multi-faceted biological effects of swimming training on enhancing muscular fitness—including muscle strength, endurance, and power—as well as sport-specific explosive power, through pathways such as remodeling of muscular morphology, metabolic functional adaptations, optimization of neural drive, and synergistic force transmission. Finally, based on the training effects, the study proposes systematic optimization directions, which include precise regulation of aquatic training variables, integrated land-water training models, and dynamic assessment and prediction of muscular function, with the aim of providing a theoretical foundation for improving the specificity and scientific rigor of specialized physical training for college swimmers.

Keywords: specialized swimming training; muscular fitness; explosive power; neuromuscular adaptation; force transmission; periodized training.

Introduction

Enhancing muscular fitness and explosive power among college students represents a critical dimension for optimizing their athletic performance and promoting physical health. Due to the specific environmental and kinematic characteristics of swimming, this form of training holds unique value in inducing neuromuscular adaptations. However, the pathways and underlying mechanisms through which it exerts its influence have not been systematically reviewed or thoroughly elucidated within this specific population. Existing research has predominantly focused on either athletic performance or isolated physiological indicators, often lacking an integrated investigation into the synergistic development of muscular fitness and explosive power. Furthermore, these studies have not adequately incorporated the combined characteristics of training load, aquatic environment, and movement patterns inherent in swimming practice. Therefore, from the perspectives of exercise physiology and biomechanics, a systematic investigation into the mechanisms by which specialized swimming training affects muscular fitness and explosive power in college students will not only deepen the theoretical understanding of aquatic exercise adaptation but also provide essential academic support for designing efficient and scientifically grounded specialized physical conditioning programs for swimmers. This underscores the clear research necessity and theoretical significance of the present study.

1. Physiological Basis and Loading Characteristics of Specialized Swimming Training

1.1 Biomechanical Mechanisms and Energy Metabolism Characteristics of Swimming

Swimming is a non-supportive cyclic activity in which the human body propels itself by overcoming multiple forms of resistance in an aquatic medium. The core biomechanical mechanism lies in the efficient transfer of force generated by limb movements to the water, creating propulsion to overcome frontal resistance, pressure differential resistance, and frictional resistance. The generation of

propulsive force relies on the synergistic application of lift and drag principles, specifically manifested in the S-pattern pull path of the upper limbs and the whip-like kicking action of the lower limbs. The effectiveness of this propulsion depends on the optimized combination of stroke efficiency, stroke rate, and stroke length. During movement, a streamlined body position and the stability of the core muscles are critical biomechanical factors for reducing resistance and ensuring the continuity of force transmission.

The energy metabolism of swimming exhibits a hybrid characteristic dominated by the aerobic system, with intermittent participation of anaerobic systems. Due to the heat-dissipating nature of the aquatic environment, the hydrostatic pressure effect, and restricted breathing, the cardiovascular and respiratory systems bear specific loads, manifested as a redistribution of cardiac output and increased work by the respiratory muscles. Different strokes and distances correspond to differentiated metabolic demands. Short-distance events rely more on the phosphagen and glycolytic systems to output peak power, while middle- and long-distance events are highly dependent on the efficiency of the aerobic oxidative system and the capacity for fat mobilization. This metabolic profile determines that swimming training provides a profound stimulus to the body's utilization of energy substrates, lactate clearance, and cardiopulmonary function^[1].

1.2 Load Structure and Intensity Control in the Periodization of Specialized Swimming Training

The load structure of specialized swimming training is a system involving the coordinated regulation of multiple variables. Its constituent elements include training volume (quantified by swimming distance), training intensity (defined by pace, heart rate, or blood lactate concentration), training density (rest interval duration), and training frequency. Within the framework of modern training periodization theory, the load structure is dynamically adjusted according to the objectives of the preparatory, competitive, and transition phases. The preparatory phase focuses on building an aerobic base and developing movement automatization through high-volume training and technical refinement. The competitive phase, in contrast, aims to achieve the peak conversion of sport-specific metabolic capacity and neuromuscular adaptations through high-intensity interval training, repetition training, and race-pace training.

Intensity control serves as the core component for achieving precise training objectives. In practice, intensity zoning models based on individual anaerobic threshold, percentage of maximal oxygen uptake, or critical speed are commonly employed to delineate the physiological adaptation targets of different load intensities. For instance, the development of aerobic endurance primarily focuses on sub-threshold intensity zones, whereas the enhancement of anaerobic capacity relies on training stimuli that reach or exceed the intensity of the maximal lactate steady state. The quantitative monitoring and dynamic adjustment of training load depend on the continuous tracking of athletes' physiological and biochemical indicators (such as blood lactate and blood urea nitrogen) as well as training data. This process aims to achieve a balance between load and recovery, thereby preventing overtraining and promoting supercompensation^[2].

1.3 Unique Stimulation of the Neuromuscular System by the Aquatic Resistance Environment

The multi-dimensional and variable resistance provided by the aquatic environment imposes unique stimuli on the neuromuscular system that are difficult to replicate in land-based training. With a density approximately 800 times that of air, water presents significant resistance to limb movement in any direction. This omnidirectional resistance characteristic demands more refined co-contraction and control among agonist and antagonist muscles, as well as between synergist and stabilizer muscle groups. Consequently, it deeply activates the core muscles and deeper stabilizing muscles, enhancing torso rigidity and the efficiency of force transmission. This continuous demand for stability forms an important foundation for developing swimming-specific muscular fitness.

The fluid properties of water result in a non-linear relationship between movement speed and resistance, meaning that an increase in motion speed leads to a squared increase in resistance. This compels the nervous system to precisely regulate the number of recruited motor units, their firing frequency, and the activation timing among different muscle groups based on real-time changes in resistance, in order to optimize force output. Long-term training can induce the nervous system to develop efficient motor programs, thereby improving inter-muscular coordination. Simultaneously, the buoyancy of water partially counteracts gravity, altering the load-bearing stress on joints and the force production patterns of muscles. This provides unique conditions for developing strength and endurance

in the periarticular muscle groups under a reduced-load state, which holds specific value for preventing sports injuries and facilitating recovery.

2. Analysis of the Pathways Through Which Swimming Training Affects Muscular Fitness and Explosive Power

2.1 Adaptations in Muscle Morphology, Structure, and Metabolic Function Induced by Swimming Training

Long-term systematic specialized swimming training can induce profound and specific adaptations in skeletal muscle at both the morphological and metabolic levels. Morphologically, training primarily promotes selective hypertrophy of slow-twitch (Type I) and fast oxidative (Type IIa) muscle fibers, which aligns with the metabolic demands of swimming as a sustained, submaximal intensity, prolonged duration activity. This adaptive change not only increases the muscle's cross-sectional area but also enhances the contractile force and fatigue resistance of individual muscle fibers by promoting the synthesis and alignment density of myofibrils, optimizing sarcomere structure, and regulating the expression of myosin heavy chain isoforms. Concurrently, the stiffness and elasticity of connective tissues, such as tendons and fascia, are also adaptively enhanced to more efficiently store and release elastic energy, thereby establishing a crucial morphological and mechanical foundation for the output of explosive power^[3].

At the metabolic functional level, swimming training, through the sustained oxidative stress stimulus on muscle cells, significantly remodels their metabolic phenotype. This adaptation manifests as enhanced mitochondrial biogenesis within the muscle cells, increased mitochondrial volume and cristae density, and a significant improvement in the capillary-to-fiber ratio (C/F ratio). These changes are accompanied by the upregulation of oxidative enzyme system activities (such as citrate synthase and β -hydroxyacyl-CoA dehydrogenase) and increased expression of fatty acid transport proteins. These comprehensive alterations substantially elevate the muscle's oxidative phosphorylation capacity and energy conversion efficiency, thereby delaying the premature mobilization of the glycolytic system. For explosive power performance, this robust aerobic metabolic foundation not only accelerates the resynthesis rate of phosphocreatine following high-intensity exercise but also enhances the tissue's lactate clearance and buffering capacity, thereby ensuring the metabolic stability and recovery efficiency of repetitive, high-intensity muscle contractions.

2.2 Optimization of Neural Drive and Motor Unit Recruitment Patterns through Aquatic Environment Training

The non-linear, multi-dimensional resistance provided by the aquatic environment imposes unique demands on the neuromuscular control system, thereby driving profound neural adaptations. To effectively overcome water resistance-which increases with the square of speed-and generate maximal propulsive impulse, the central nervous system must develop highly coordinated and precisely timed inter-muscular activation patterns. This process involves the enhancement of sensorimotor integration, whereby the central nervous system continuously refines motor commands by processing proprioceptive feedback from muscle spindles, Golgi tendon organs, and cutaneous receptors. Long-term training can strengthen the efficiency of spinal central pattern generators and enhance the task-specific representation within the motor cortex of the brain. This leads to the formation of more economical and biomechanically efficient swimming-specific neuromuscular control strategies, reducing the level of co-activation between agonist and antagonist muscles.

At the level of motor unit recruitment, the unique mechanical properties of water compel the nervous system to optimize its mobilization strategy. To overcome peak resistance during the brief, crucial acceleration phase of the stroke, the nervous system needs to develop extremely rapid recruitment rates and a high degree of synchronization of motor units. This allows for the instantaneous recruitment of the entire motor unit pool, including high-threshold Type IIx muscle fibers. This repeated, precise mobilization and high-frequency stimulation of high-threshold motor units directly enhances the excitability of α -motor neurons, synaptic efficacy, and the post-activation potentiation of muscles. Consequently, it improves the muscle's maximal voluntary contraction capacity and rate of force development, which constitute the neurological core of explosive power performance. Meanwhile, the buoyant support of water reduces the demand for anti-gravity efforts, allowing the nervous system to focus on force production patterns aimed at overcoming water resistance under more optimal initial

muscle lengths and joint angles. This likely facilitates a dissociated improvement in force application technique and neural drive efficiency.

2.3 Synergistic Development Mechanism between the Periodicity of Swimming Movements and the Transmission of Explosive Power

The expression of explosive power in swimming is not a simple summation of the peak force from isolated muscle groups. Instead, it is the comprehensive result of the coordinated operation of the whole-body kinetic chain within a strict spatiotemporal sequence, which transmits force in an orderly manner to the point of interaction with the water. The periodic nature of swimming movements dictates that each arm stroke and leg kick must complete a full mechanical cycle—from acceleration to deceleration—within a limited phase. Its effectiveness depends on the average propulsive force rather than the instantaneous peak force. Training solidifies the activation sequence, intensity, and duration of various muscle groups (from the core of the torso to the distal limbs) within each stroke cycle. This achieves a precise match between the peak of force generation and the optimal mechanical body position (such as the high-elbow catch), thereby maximizing the positive impulse of each movement cycle^[4].

The effective transmission of explosive power in an aquatic medium is highly dependent on the proximal stiffness established by core stability and the coordination of the kinetic chain. The core muscles, serving as the mechanical hub connecting the momentum of the upper and lower limbs, create a stable mechanical platform for explosive limb force production through their pre-activation and isometric contraction capabilities, thereby preventing energy dissipation. Swimming training, through sustained, multi-planar trunk resistance and anti-rotational loading, significantly increases the recruitment threshold and endurance of deep stabilizing muscles such as the transversus abdominis, pelvic floor muscles, and multifidus. This enhances the trunk's capacity to act as a rigid body for transmitting both rotational and linear momentum. Consequently, the explosive power developed through swimming is a highly specialized "transmission-oriented" type. Its ultimate expression depends not only on the peak torque of the distal segments but, more critically, on the efficiency of force transmission—initiated from the core and delivered to the extremities through a closed kinetic chain—as well as on the fluidity of momentum transfer between the upper and lower limbs. This synergistic development mechanism of the neuro-mechanical system constitutes the fundamental characteristic that distinguishes swimming-specific explosive power from the explosive power generated in land-based single-joint or open-chain exercises.

3. Optimization of Training Protocols and Directions for Physiological Adaptation Based on Training Effects

3.1 Precise Regulation Strategies of Swimming Training Variables to Enhance Muscular Fitness

Enhancing muscular fitness requires the systematic deconstruction and precise regulation of multiple variables within swimming training, with the core objective being the accurate alignment of physiological stimuli with intended adaptations. The definition of training intensity must extend beyond mere pace standards by integrating individual physiological parameters such as blood lactate concentration, heart rate variability, and ratings of perceived exertion. This integration facilitates the establishment of intensity zone models corresponding to distinct energy metabolic pathways and muscle fiber recruitment patterns. For the development of muscular aerobic endurance, the focus should be on sustained or intermittent loads performed near the individual lactate threshold intensity. This approach maximizes the stimulation for muscle capillarization and mitochondrial biogenesis, thereby improving muscular oxygen utilization efficiency and fatigue resistance. For the enhancement of maximal strength and power, it is necessary to incorporate short-distance, supramaximal effort sprint training or resistance swimming utilizing equipment such as hand paddles or resistance parachutes. Such training aims to fully recruit high-threshold type II muscle fibers and increase the frequency and synchronization of neural drive, directly targeting the neuromuscular functions required for explosive power with an overload stimulus.

The periodized distribution of training volume is key to achieving long-term adaptation and the transformation towards peak functional performance. Through cumulative high-volume training phases within a macrocycle, the metabolic and morphological foundation of the muscle is systematically built. Subsequently, during the competition preparation period, a structural reduction in training volume

coupled with maintained or increased training intensity, alongside appropriate nutritional and recovery strategies, guides muscular function towards supercompensation and peak adaptation. The balance between training frequency and recovery is paramount. Full consideration must be given to the high-repetition stress characteristics of aquatic environment training on areas such as the shoulder joint complex. Water-based training sessions and recovery days should be scientifically scheduled to prevent overuse injuries and ensure the continuity of the adaptation process. Furthermore, the principle of biomechanical specificity in training content cannot be overlooked. For instance, specialized technical drills emphasizing the high-elbow catch position and the final acceleration phase of the push can specifically strengthen the posterior shoulder girdle muscles and upper limb extensors in terms of eccentric control and concentric explosive power at specific joint angles. This approach facilitates the synergistic development of technical economy and muscular fitness^[5].

3.2 Integrated Training Models for Explosive Power Incorporating Land-Based Compensatory Exercises

The expression of explosive power in swimming is constrained by the physical limitations of the aquatic environment on the rate of force development and absolute peak force. Therefore, constructing integrated training models that incorporate land-based compensatory exercises has become a necessary approach to overcome existing performance plateaus. The core objective of land-based training is to develop the capacity of the swimming-specific kinetic chain to generate maximal voluntary contraction force and maximal rate of force development without the support of buoyancy. This aims to compensate for the insufficient stimulus intensity for maximal strength and rapid strength production provided by water-only training to the neuromuscular system. This primarily involves high-load foundational strength training targeting the core prime movers in swimming, such as the latissimus dorsi, pectoralis major, core stabilizers, and lower-limb hip extensors. Examples include weighted pull-ups, bench presses, and variations of squats. The goal is to increase muscle cross-sectional area and enhance the mobilization potential of motor units, thereby establishing a solid mechanical foundation for power output in the water.

The key to achieving efficient transfer of training effects lies in ensuring that the kinetic and kinematic characteristics of land-based exercises closely align with those of sport-specific movements in water. The design should simulate the coordinated sequence of the swimming kinetic chain and the force-time curve characteristics. For instance, standing cable or elastic band resistance exercises can be used to mimic the acceleration trajectory of the pull, while medicine ball overhead throws can train the explosive power of trunk rotation. Plyometric training (e.g., box jumps, combined resistance/assisted sprints) is employed to enhance the reactive strength of the neuromuscular system and the efficiency of the stretch-shortening cycle. This is crucial for improving instantaneous explosive power required during starts off the block, turns off the wall, and the initial phase of the stroke, where inertia or still water must be rapidly overcome. The integration of land-based and aquatic training must adhere to the principle of synergistic periodization. This ensures that the foundational strength and power gains achieved on land can be effectively transformed into improvements in propulsive force output efficiency during the water-based technical training cycles. This transformation occurs through the repeated reinforcement and refined control of sport-specific movement patterns, ultimately facilitating the organic conversion of non-specific neuromuscular adaptations into highly specialized athletic performance.

3.3 Dynamic Assessment and Prediction of Muscular Function Performance Following Long-Term Swimming Training

The evaluation of muscular function performance after long-term swimming training should employ a multi-dimensional, dynamic system of physiological and biomechanical indicators. This physiological assessment extends beyond singular tests such as maximal oxygen uptake or lactate threshold, encompassing the muscular functional level. It includes the evaluation of the maximum torque, power, and endurance ratios of the shoulder and knee joint flexor and extensor muscle groups through isokinetic strength testing. It also utilizes surface electromyography to analyze the activation timing, amplitude, and fatigue index of key muscle groups. Furthermore, it incorporates morphological measurements of muscles (such as ultrasound assessments of muscle thickness and pennation angle) and the monitoring of metabolic biomarkers. Together, these indicators delineate the dynamic trajectory of changes in attributes related to muscular fitness and explosive power^[6].

Building predictive models for muscular function performance based on the accumulation of

longitudinal data represents a forward-looking direction. Such models can integrate initial functional baselines, training load characteristics (e.g., impulse, monotony, strain), genetic factors, and recovery indicators (e.g., heart rate recovery, variability). By utilizing machine learning algorithms, these models can identify key variables influencing adaptation outcomes and their interactions. The purpose of this model is to achieve personalized training feedback, predicting the potential adaptation level and time course of an individual's muscular function under specific training interventions. It also aims to provide early warnings for preventing sports injury risks caused by muscular strength imbalances or excessive fatigue, thereby facilitating a paradigm shift in training program design from an experience-based approach to a precise and scientific one.

Conclusion

This study demonstrates through systematic analysis that specialized swimming training, by virtue of its unique physiological load and biomechanical environment, can effectively induce multi-level adaptive changes in college students. These changes include selective muscular hypertrophy, enhanced metabolic function, optimized neural drive, and improved kinetic chain synergy. Collectively, these adaptations lead to a comprehensive improvement in their muscular fitness and sport-specific explosive power in water. The key to enhancing training effectiveness lies in the precise periodized regulation of aquatic training variables, supplemented by land-based compensatory strength and power training designed to offset the limitations of the aquatic environment, thereby forming an integrated training model. Future research should focus on establishing a multi-dimensional dynamic assessment system for muscular function under long-term training and exploring predictive models of adaptation based on individual differences and training load data. This will advance swimming physical conditioning towards a more personalized and precise direction.

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