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Role of Flexibility Development in Improving Stroke Length, Propulsion, and Swimming Velocity among Adolescent Swimmers

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Abstract: *Flexibility improves stroke efficiency, propulsion, and swimming velocity among other physiological and biomechanical aspects. This study examines how flexibility development improves stroke length, propulsion, and swimming velocity in adolescents. Rapid physical growth and neuromuscular development in adolescence are perfect for improving flexibility, which may improve swimming technique and performance. Swimmers may swim longer, more efficient strokes, lower drag, and propel themselves better with more shoulder, hip, ankle, and trunk joint flexibility. Flexibility training treatments will be compared to stroke length, stroke rate, propulsion efficiency, and swimming speed. Adolescent swimmers from competitive training programs will undergo flexibility and swimming performance tests before and after the intervention period in a structured experimental design. Statistical analysis will evaluate how much flexibility improves performance and if various flexibility components affect swimming biomechanics more. The results should help coaches, sports scientists, and physical education professionals build evidence-based training programs to improve swimming performance throughout development. The findings may also help explain how flexibility development affects swimming performance and long-term success*

Keywords: Flexibility, stroke length, propulsion, swimming velocity, adolescent swimmers, biomechanics, range of motion

I. INTRODUCTION

1.1 Background and Context

Swimming performance is a multifactorial construct influenced by biomechanical, physiological, anthropometric, and technical variables. Among these, the role of flexibility—defined as the range of motion (ROM) available at a joint—has garnered increasing attention in sports science research. For adolescent swimmers, who are undergoing rapid physical development, the development of flexibility may be particularly consequential for both performance enhancement and injury prevention.

The biomechanical demands of competitive swimming require athletes to achieve specific joint positions to minimize hydrodynamic drag while maximizing propulsive forces. Flexibility across multiple joints—particularly the shoulders, ankles, hips, and spine—influences the ability to achieve optimal body positions in the water, efficiently apply force, and reduce the risk of overuse injuries. Early engagement in flexibility training, especially during developmental windows between ages 6 and 11, can optimize joint ROM increases, enhancing overall athleticism and performance in the water.

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1.2 The Swimming Performance Triad: Stroke Length, Propulsion, and Velocity

Swimming velocity is fundamentally determined by the product of stroke rate (SR) and stroke length (SL), as expressed in the classical equation:

$$v = SR \times SL$$

where v represents swimming velocity, SR is the number of strokes per unit time, and SL is the distance covered per stroke cycle. While stroke rate is influenced by neuromuscular coordination and power output, stroke length is more directly affected by anthropometric characteristics, technical efficiency, and joint flexibility.

Propulsion, the force that propels the swimmer forward, is generated through coordinated movements of the upper and lower limbs. The propulsive impulse (I+) during a swimming cycle can be expressed as:

$$I+ = \int F(t)\, dt$$

where F(t) represents the time-dependent force applied to the water. Greater propulsive impulse requires both the ability to apply force effectively and the capacity to maintain an optimal body position throughout the stroke cycle.

1.3 The Adolescent Swimmer: A Distinct Population

Adolescent swimmers (typically defined as ages 13-17) represent a unique population for flexibility research. During this developmental period, swimmers experience significant changes in stature, limb length, muscle mass, and joint mechanics. The adolescent growth spurt, characterized by rapid increases in height and limb length, can temporarily disrupt coordination and technique, making flexibility training particularly valuable for maintaining or improving performance.

Research indicates that young swimmers are able to increase in-water forces by 16-24% over a competitive season, with improvements in force production more evident in the first macrocycle of training. However, the specific contribution of flexibility development to these force enhancements remains unclear.

1.4 Problem Statement

Despite the theoretical importance of flexibility for swimming performance, several critical gaps exist in the current literature:

1. **Inconsistent Evidence:** While some studies demonstrate strong correlations between joint mobility and swimming speed (e.g., shoulder flexion-extension ROM correlating with swimming velocity at $r = 0.905$), others report non-significant relationships.
2. **Limited Longitudinal Data:** Most existing research employs cross-sectional designs, limiting understanding of how flexibility development over time influences performance changes.

1.5 Research Questions

This dissertation will address the following primary research questions:

1. **RQ1:** What is the relationship between joint flexibility (shoulder, ankle, hip, and spine) and stroke length in adolescent swimmers?
2. **RQ2:** To what extent does flexibility development influence propulsive force production (measured via tethered swimming tests)?

1.6 Research Hypotheses

Based on the existing literature, the following hypotheses are proposed:

H1: Greater shoulder flexion-extension ROM will be significantly and positively correlated with stroke length ($r > 0.70$).

H2: Improved ankle plantar-flexion ROM will correlate with enhanced propulsive force during underwater undulatory swimming (UUS).

1.7 Significance of the Study

This research holds significance for multiple stakeholders:

For Coaches and Practitioners: Findings will provide evidence-based guidance for incorporating flexibility training into adolescent swim programs, including recommendations for joint-specific exercises, training frequency, and integration with in-water practice.

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For Sport Scientists: The study will contribute to the theoretical understanding of how flexibility influences swimming biomechanics, particularly the mechanisms linking ROM to propulsive force and stroke kinematics.

For Swimmers: Improved understanding of flexibility-performance relationships will enable athletes to make informed decisions about supplementary training activities.

For Policy Makers: Results may inform national-level swimming development programs, particularly regarding talent identification and long-term athlete development pathways.

1.8 Delimitations and Scope

This study is delimited to:

- Adolescent competitive swimmers aged 13-17 years
- Front-crawl (freestyle) swimming performance
- Flexibility at four key joint complexes (shoulder, ankle, hip, and spine)
- Performance metrics including stroke length, propulsive force, and swimming velocity
- A 12-week intervention period

II. LITERATURE REVIEW

2.1 Biomechanical Foundations of Swimming Performance

2.1.1 Hydrodynamic Principles

Swimming performance is governed by the fundamental interaction between propulsive forces and resistive forces (drag). When swimming at a constant speed, the following relationship applies according to Newton's first law:

$$F_{prop} = F_{drag}$$

where Fprop represents the propulsive force generated by the swimmer and Fdrag represents the resistive force of the water. Drag force in swimming can be approximated by:

$$F_{drag} \approx k \cdot S \cdot V^{1.8-2.2}$$

where k is a constant, S is the wetted surface area, and V is swimming velocity.

The implication of these equations is that as swimming velocity increases, drag increases exponentially, requiring proportionally greater propulsive force. This creates a performance paradox: swimmers must generate sufficient propulsive force to overcome drag while maintaining an efficient body position that minimizes drag.

2.1.2 The Swim Cycle and Propulsive Impulse

Within each swim cycle, speed fluctuations occur as swimmers alternate between propulsive and non-propulsive phases. The propulsive impulse generated during a cycle is defined as the time integral of propulsive force:

$$I+ = \int F(t)\, dt$$

The total propulsive impulse over n cycles is:

$$I+ = n \times (I+_{right\ arm} + I+_{left\ arm} + I+_{right\ leg} + I+_{left\ leg})$$

The average force over n cycles can be calculated as:

$$F_{av} = \Sigma\, I(i)+ / T$$

where T is the cycle period. However, it is important to note that only part of the force generated contributes to propulsion; part of this force provides kinetic energy to the water without propelling the swimmer forward.

2.1.3 Stroke Kinematics: Rate, Length, and Index

The relationship between stroke rate and stroke length has been extensively studied in swimming biomechanics. Research demonstrates that expert swimmers are able to maintain a more consistent relative contribution of movement harmonics to the overall force spectrum, suggesting greater movement efficiency.

2.2 Flexibility in Swimming: Theoretical Framework

2.2.1 Joint Flexibility and Movement Efficiency

Flexibility is considered an integral component of physical conditioning for swimmers, whereby increased ROM at key joints may improve swimming movement efficiency and reduce injury risk. However, excessive flexibility without adequate muscular control may be detrimental to performance.

The theoretical mechanism linking flexibility to performance is based on the following pathways:

1. **Improved Kinematic Range:** Greater ROM allows swimmers to achieve optimal joint positions for force application, potentially increasing stroke length and reducing drag.
2. **Enhanced Force Production:** Improved flexibility may enable more effective force application by allowing muscles to operate at optimal length-tension relationships.
3. **Reduced Energy Cost:** Better flexibility may reduce the energy cost of swimming by improving movement fluidity and reducing internal resistance.
4. **Injury Prevention:** Adequate flexibility reduces injury risk, allowing for more consistent training and performance.

2.2.2 Joint-Specific Flexibility Requirements

Different swimming strokes place different demands on joint flexibility. For front-crawl (freestyle), the primary focus is on:

Shoulder Flexibility: The shoulder complex is critical for the recovery and propulsive phases of the arm stroke. Shoulder mobility—particularly flexion, extension, and rotation—directly influences stroke mechanics and propulsion. Research demonstrates strong correlations between shoulder flexion-extension ROM and swimming speed ($r = 0.905$) in sub-elite adolescent swimmers.

Ankle Flexibility: Ankle range of motion, particularly plantar flexion, is essential for effective kicking and streamlined body position. Simulation studies have shown that increased ankle plantar-flexion ROM positively affects streamwise force time histories during and after the downbeat. However, the relationship between ankle flexibility and performance has shown inconsistent results in empirical studies.

Core Flexibility: The core musculature connects the upper and lower body, enabling effective force transmission. Core flexibility may influence the ability to maintain streamlined body position and generate whole-body undulation.

2.3 Empirical Evidence: Flexibility and Swimming Performance

2.3.1 Shoulder Mobility and Performance

Recent research using three-dimensional biomechanical analysis has provided strong evidence for the importance of shoulder mobility. A cross-sectional study of 16 sub-elite adolescent swimmers (mean age 14.94 ± 1.81 years) found:

- Swimming speed had strong and significant positive correlations with flexion-extension ROM ($r = 0.905$)
- Right-side adduction ($r = 0.981$) demonstrated very strong correlations with swimming speed
- Total abduction-adduction range showed comparable correlations ($r = 0.981$)
- Left-side mobility metrics demonstrated weaker or non-significant correlations

These findings highlight the biomechanical importance of dominant-limb shoulder mobility in enhancing swimming propulsion. The findings also suggest that bilateral asymmetry may reflect functional adaptations rather than impairments.

In terms of stroke kinematics, the same study found a negative correlation with stroke frequency ($r = -0.843$) and a positive correlation with stroke length ($r = 0.830$). This suggests that greater shoulder mobility enables swimmers to achieve longer strokes, reducing the reliance on high stroke rates.

2.3.2 Ankle Flexibility and Propulsion

Research on ankle flexibility presents a more complex picture. A study of 20 national-level male swimmers aged 14-18 years investigated the effects of ankle flexibility training on propulsion. While the 6-week training program significantly improved ankle plantar-flexion flexibility (left foot $p = 0.0008$; right foot $p = 0.0131$), the improvement in 25m kick sprint times was not significant ($p = 0.4027$). The authors suggested that the 25m test distance may have been insufficient to detect changes in speed, and that longer distances might better demonstrate the performance benefits of improved ankle flexibility.

2.3.3 Flexibility Training Interventions

A 6-week intervention study using elastic resistance band training in adolescent swimmers found that dry-land strengthening and core stability training improved shoulder stability and technical efficiency, as evidenced by a significant decrease in stroke rate during short-distance power tests (59.57 ± 3.47 to 55.94 ± 4.91 strokes/min, p =

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0.028). However, swimming speed remained unchanged, and no significant changes were found in pectoralis minor muscle length.

These findings suggest that while flexibility training may improve technical efficiency, the transfer to actual swimming speed may require longer training periods or integration with specific in-water practice.

2.4 Anthropometric and Biological Considerations

2.4.1 Growth and Development in Adolescent Swimmers

Adolescent swimmers undergo significant anthropometric changes that affect performance. Research tracking young swimmers over a competitive season has shown that performance improvements are associated with:

- Increases in hand surface area (both dominant and non-dominant)
- Increases in stature and arm span
- Improvements in in-water force production (16-24% increase over the season)

The developmental stage of swimmers has implications for flexibility training. During growth spurts, limb length increases can temporarily disrupt technique, making flexibility training particularly valuable.

2.4.2 Sex Differences

Sex differences in flexibility and swimming performance are well-documented. Research on underwater undulatory swimming (UUS) found that boys had significantly greater velocity (1.35 m/s vs. 1.24 m/s), greater distance per cycle (0.74 m vs. 0.67 m), and higher toe amplitude (0.63 m vs. 0.58 m), but smaller ankle joint ROM (57° vs. 64°).

Despite these differences, the relationships between kinematic variables and velocity were identical for both sexes, suggesting that UUS technical training can be performed without gender-division. However, flexibility training programs may need to account for sex-specific baseline flexibility levels.

2.5 Theoretical Models: Coordination and Adaptability

2.5.1 Newell's Constraints Model

Adaptability in swimming relates to a subtle blend between stability (persistent behavior) and flexibility (variable behavior). According to Newell's model, three categories of constraints shape human movement behavior:

1. **Task Constraints:** The goal of swimming as fast as possible over a fixed distance
2. **Environmental Constraints:** Physical variables such as water density and drag

Flexibility development can be understood as modifying organismic constraints to enable more effective responses to task and environmental demands.

2.5.2 The Adaptability-Flexibility Nexus

Swimmers must adapt their movement patterns to varying speeds and conditions. When swimming faster, swimmers increase stroke rate, the percentage of time devoted to propulsion within a cycle, and the index of coordination (IdC). However, the capacity to increase stroke length while maintaining stroke rate depends on flexibility and other factors.

Expert swimmers demonstrate greater adaptability, maintaining the relative contribution of the main harmonics to the overall force spectrum despite changes in speed. This suggests that flexibility development may contribute to improved adaptability by enabling a wider range of effective movement solutions.

2.6 Research Gaps and Justification for Current Study

Despite the existing literature, several important gaps remain:

1. **Longitudinal Studies:** Most evidence on flexibility-performance relationships is cross-sectional. There is limited longitudinal research tracking changes in flexibility and performance concurrently.
2. **Integrated Biomechanical Assessment:** Few studies have simultaneously examined kinematic (stroke length) and kinetic (propulsive force) responses to flexibility training.
3. **Adolescent-Specific Research:** The unique developmental characteristics of adolescent swimmers have not been adequately considered in flexibility research.
4. **Mediation Effects:** The mechanisms linking flexibility to performance (e.g., through stroke length or propulsion) have not been statistically tested.

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5. **Sex-Specific Analysis:** While sex differences are observed, few studies have adequately powered analyses to examine sex-specific effects.
6. **Dose-Response Relationships:** No studies have systematically examined the volume and intensity of flexibility training needed to optimize performance.

The current study addresses these gaps through a longitudinal mixed-methods design incorporating comprehensive biomechanical assessments.

III. METHODOLOGY

3.1 Research Design

This study employs a mixed-methods longitudinal design combining:

1. **Quantitative Component:** A 12-week quasi-experimental intervention with pre-, mid-, and post-tests
2. **Qualitative Component:** Semi-structured interviews with coaches and participants, and observational analysis of training sessions

The quantitative component utilizes a two-group (intervention and control) design with repeated measures at three time points (baseline, 6 weeks, 12 weeks). The qualitative component will contextualize quantitative findings and explore implementation issues.

3.2 Participants

3.2.1 Sample Size and Recruitment

A total of 80 adolescent competitive swimmers will be recruited from swimming clubs in [City/Region]. Sample size calculation was based on a power analysis ($\alpha = 0.05$, $\beta = 0.80$) for a mixed-model ANOVA with repeated measures (three time points, two groups), anticipating a moderate effect size ($\eta^2 = 0.06$). This yielded a minimum sample of 60 participants; 80 participants will be recruited to account for attrition.

3.2.2 Inclusion Criteria

- Age 13-17 years
- Minimum competitive experience of 3 years
- Training frequency ≥ 4 sessions per week

3.2.3 Exclusion Criteria

- History of shoulder, hip, or ankle surgery
- Current musculoskeletal injury affecting training
- Medical conditions affecting joint mobility
- Concurrent participation in other flexibility-focused interventions (e.g., yoga, gymnastics)

3.2.4 Participant Characteristics

Based on the target population, anticipated participant characteristics include:

Characteristic	Males (n=40)	Females (n=40)
Age (years)	15.1 ± 1.4	15.0 ± 1.5
Stature (cm)	171.3 ± 8.2	162.8 ± 6.5
Body Mass (kg)	62.5 ± 9.8	55.2 ± 7.4
Training Experience (years)	5.8 ± 1.9	5.9 ± 1.8

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3.3 Instrumentation and Measures

3.3.1 Flexibility Assessment

Shoulder Flexibility: Three-dimensional shoulder ROM will be measured using markerless motion-capture (VALD HumanTrak™), recording bilateral flexion, extension, abduction, adduction, and rotational ranges, with a reported accuracy of ±2°.

Ankle Flexibility: Ankle ROM, including dorsiflexion and plantar-flexion, will be measured using a standard goniometer, following established protocols. Measurements will be taken in both passive and active conditions.

Hip and Spinal Flexibility: Hip flexion, extension, abduction, and spinal rotation will be measured using goniometry and inclinometry. The sit-and-reach test will be used as a global measure of hamstring and lower back flexibility.

3.3.2 Kinematic Assessment

Stroke Length and Stroke Rate: Underwater video analysis using three synchronized 50-Hz cameras will be employed to derive stroking parameters. SL ($m \cdot cycle^{-1}$) and SI ($m^2 \cdot s^{-1} \cdot cycle^{-1}$) will be calculated from mean speed (v) and SR.

Index of Coordination (IdC): The time gap between propulsion of the two arms will be expressed as a percentage of the duration of the complete arm stroke cycle. IdC will be calculated as the mean of IdCleft and IdCright.

Propulsive Phase Duration: The total propulsive phase duration (pull and push) will be expressed both in seconds and as a percentage of the cycle time (PrP%).

3.3.3 Kinetic Assessment

Tethered Swimming Force: A tethered swimming system will measure in-water force production during maximal effort bouts. Force data will be sampled at 1000 Hz using a calibrated load cell. The following parameters will be extracted:

- Mean peak force (Freax)
- Subsequent peak force (SFreax)
- Symmetry index (SyI)

Propulsive Impulse: Force-time integration will be used to calculate propulsive impulse (I+) over the swim cycle, following established methodology from Takagi and Wilson.

3.3.4 Performance Assessment

Swimming Velocity: Participants will perform maximal effort 50m, 100m, and 200m front-crawl time trials in a 25m pool. Times will be recorded using electronic timing pads and confirmed with manual stopwatches.

Stroke Index: Calculated as SL × v, providing a measure of stroke efficiency.

Distance Per Stroke (DPS): Calculated as distance / number of strokes, providing a practical measure of stroke length.

3.3.5 Anthropometric Assessment

Standard anthropometric measurements will be collected according to International Society for Advancement of Kinanthropometry (ISAK) protocols:

- Arm span (cm)
- Hand surface area (cm^2)
- Limb segment lengths

3.4 Intervention Protocol

3.4.1 Intervention Group

Participants in the intervention group will receive 12 weeks of supplementary flexibility training in addition to their regular swim training (which typically includes 6-8 in-water sessions per week). The flexibility program will include:

Warm-Up Component (10-15 minutes, before each session):

- Dynamic arm swings: 30 seconds to 1 minute per set
- Dynamic leg swings: 10-15 swings per leg per direction
- Dynamic ankle circles: 10 clockwise, 10 counterclockwise per ankle
- Dynamic torso rotations

3.4.2 Control Group

Participants in the control group will continue their regular training without supplementary flexibility exercises. They will be offered the flexibility training program after the study completion.

3.5 Data Collection Procedures

3.5.1 Timeline

Time Point	Week	Measures
Pre-test	0	All flexibility, kinematic, kinetic, and performance measures; anthropometrics
Mid-test	6	Flexibility, kinematic, and performance measures
Post-test	12	All flexibility, kinematic, kinetic, and performance measures

3.5.2 Testing Protocol

Each testing session will be conducted over two days:

Day 1:

- Anthropometric measurements
- Flexibility assessments
- Dry-land familiarization

Day 2:

- In-water performance trials (50m, 100m, 200m)
- Kinematic video analysis
- Tethered swimming test

3.5.3 Standardization

All testing will be conducted:

- At the same time of day (± 1 hour)
- With standard warm-up procedures (15 minutes of controlled swimming)
- In a 25m indoor pool at standard temperature (27-28°C)
- Under consistent lighting and environmental conditions

3.6 Statistical Analysis

3.6.1 Primary Analyses

Descriptive Statistics: Mean, standard deviation, range, and confidence intervals for all variables at each time point.

Repeated Measures ANOVA: Mixed-model ANOVA will assess between-group (intervention vs. control) and within-group (time) effects, with Bonferroni corrections for multiple comparisons.

Correlation Analysis: Pearson or Spearman correlation coefficients will assess relationships between flexibility variables and performance outcomes.

Regression Analysis: Multiple linear regression will identify predictors of swimming velocity and stroke length.

Mediation Analysis: Baron and Kenny's approach will test whether the relationship between flexibility and swimming velocity is mediated by stroke length and/or propulsive impulse.

3.6.2 Secondary Analyses

Sex-Based Subgroup Analysis: Independent samples t-tests will compare male and female responses to the intervention.

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Dose-Response Analysis: Compliance data will be used to examine the relationship between training dose and performance outcomes.

Effect Size: Cohen's d and partial eta-squared (η^2) will be calculated to quantify practical significance.

3.6.3 Software

Statistical analyses will be conducted using SPSS 26.0 and JASP, with significance set at $p \leq 0.05$.

IV. RESULTS

4.1 Participant Characteristics and Baseline Data

Based on participant recruitment and testing protocols, the following baseline characteristics are anticipated:

Variable	Intervention Group (n=40)	Control Group (n=40)	p-value
Age (years)	14.9 ± 1.6	15.0 ± 1.5	0.78
Training Experience (years)	5.7 ± 1.8	5.8 ± 1.9	0.82
Shoulder Flexion ROM (°)	175.3 ± 12.4	174.8 ± 11.9	0.85
Shoulder Extension ROM (°)	58.2 ± 8.6	57.9 ± 9.1	0.88
Ankle Plantar-Flexion ROM (°)	42.5 ± 6.8	43.1 ± 7.2	0.71
Swimming Velocity (50m, m/s)	1.52 ± 0.18	1.53 ± 0.17	0.80
Stroke Length (m/cycle)	1.85 ± 0.28	1.83 ± 0.26	0.74
Stroke Rate (Hz)	0.82 ± 0.09	0.83 ± 0.08	0.61

4.2 Flexibility Changes Over the Intervention

4.2.1 Shoulder Flexibility

Projected results indicate that the intervention group will demonstrate significant improvements in shoulder ROM compared to the control group:

Time Point	Intervention (°)	Control (°)	Group × Time Interaction
Pre-test	175.3 ± 12.4	174.8 ± 11.9	-
Mid-test (6 weeks)	179.8 ± 11.5	175.2 ± 12.1	p = 0.042
Post-test (12 weeks)	183.5 ± 10.8	175.5 ± 12.0	p = 0.008

These projected improvements align with the findings of Purnomo et al. (2026), who reported strong correlations between shoulder flexion-extension ROM and swimming speed (r = 0.905).

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4.2.2 Ankle Flexibility

Projected ankle plantar-flexion ROM changes:

Time Point	Intervention (°)	Control (°)	Group × Time Interaction
Pre-test	42.5 ± 6.8	43.1 ± 7.2	-
Mid-test (6 weeks)	45.2 ± 6.4	43.4 ± 7.0	p = 0.038
Post-test (12 weeks)	47.8 ± 6.1	43.6 ± 7.1	p < 0.001

These changes are expected to be statistically significant, consistent with previous ankle flexibility training studies.

4.2.3 Hip and Spinal Flexibility

Projected improvements of 5-8% in hip ROM and 10-12% in spinal rotation, consistent with comprehensive flexibility training.

4.3 Effects on Stroke Length and Kinematics

4.3.1 Stroke Length

Projected stroke length changes:

Time Point	Intervention (m/cycle)	Control (m/cycle)	Group × Time Interaction
Pre-test	1.85 ± 0.28	1.83 ± 0.26	-
Mid-test (6 weeks)	1.91 ± 0.26	1.84 ± 0.27	p = 0.036
Post-test (12 weeks)	1.97 ± 0.24	1.85 ± 0.26	p = 0.004

The projected correlation between shoulder flexion ROM and stroke length is expected to be positive and significant ($r = 0.72$-0.85), consistent with previous findings where stroke length correlated with swimming speed ($r = 0.830$).

4.3.2 Stroke Rate

Projected stroke rate changes:

Time Point	Intervention (Hz)	Control (Hz)	Group × Time Interaction
Pre-test	0.82 ± 0.09	0.83 ± 0.08	-
Mid-test (6 weeks)	0.80 ± 0.08	0.82 ± 0.09	p = 0.045
Post-test (12 weeks)	0.77 ± 0.08	0.82 ± 0.08	p = 0.002

Consistent with previous research showing that improved shoulder stability decreases stroke rate in short-distance power tests.

4.3.3 Stroke Index

Projected stroke index changes:

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Time Point	Intervention ($m^2 \cdot s^{-1} \cdot cycle^{-1}$)	Control ($m^2 \cdot s^{-1} \cdot cycle^{-1}$)	Group × Time Interaction
Pre-test	2.82 ± 0.52	2.79 ± 0.50	-
Mid-test (6 weeks)	2.99 ± 0.48	2.81 ± 0.51	p = 0.028
Post-test (12 weeks)	3.15 ± 0.45	2.83 ± 0.50	p < 0.001

4.4 Effects on Propulsion
4.4.1 Tethered Swimming Force
Projected in-water force production:

Force Parameter	Time Point	Intervention (N)	Control (N)	Group × Time Interaction
Freax D	Pre-test	48.2 ± 14.1	47.8 ± 13.8	-
	Mid-test	52.4 ± 13.5	48.5 ± 14.2	p = 0.042
	Post-test	56.1 ± 12.8	49.1 ± 14.0	p = 0.006
Freax ND	Pre-test	47.5 ± 13.8	46.9 ± 13.5	-
	Mid-test	52.8 ± 13.2	47.8 ± 14.1	p = 0.032
	Post-test	57.0 ± 12.5	48.5 ± 13.8	p = 0.004

These projections are consistent with findings that young swimmers can increase in-water forces by 16-24% over a competitive season, with the flexibility intervention potentially enhancing this effect.
4.4.2 Propulsive Impulse
Projected propulsive impulse improvements of 12-18% in the intervention group, with ankle flexibility changes mediating these improvements.
4.5 Effects on Swimming Velocity
4.5.1 100m Freestyle Velocity

Time Point	Intervention (m/s)	Control (m/s)	Group × Time Interaction
Pre-test	1.48 ± 0.17	1.49 ± 0.16	-
Mid-test (6 weeks)	1.52 ± 0.16	1.50 ± 0.17	p = 0.038
Post-test (12 weeks)	1.56 ± 0.15	1.51 ± 0.16	p = 0.005

4.5.2 50m vs. 200m Performance
Projected improvements of 2.5-3.0% in 50m times and 3.5-4.5% in 200m times for the intervention group, suggesting greater improvements in endurance events.

4.6 Mediation Analysis
Projected mediation analysis results, based on Baron and Kenny's approach:
1. **Path A:** Flexibility → Stroke Length ($\beta = 0.58$, $p < 0.001$)
2. **Path B:** Flexibility → Propulsive Impulse ($\beta = 0.46$, $p < 0.001$)
3. **Path C:** Flexibility → Velocity (Total Effect: $\beta = 0.52$, $p < 0.001$)
4. **Path C':** Flexibility → Velocity (Direct Effect: $\beta = 0.18$, $p = 0.042$)

Indirect Effects:
- Via Stroke Length: 0.21 ($p < 0.001$)
- Via Propulsive Impulse: 0.13 ($p = 0.003$)

This suggests that the relationship between flexibility and swimming velocity is partially mediated by improvements in stroke length and propulsive impulse.

4.7 Sex Differences
Projected sex differences in response to the intervention:

Measure	Males (n=40)	Females (n=40)	Interaction
Δ Shoulder ROM (°)	+8.2 ± 4.6	+10.1 ± 5.2	p = 0.038
Δ Stroke Length (m/cycle)	+0.12 ± 0.08	+0.15 ± 0.09	p = 0.042
Δ Velocity (m/s)	+0.08 ± 0.04	+0.09 ± 0.05	p = 0.053

These projections are consistent with research showing sex differences in baseline flexibility and performance responses.

4.8 Qualitative Findings

4.8.1 Perceived Benefits
Based on pilot interviews, projected themes include:
- Improved "feel for the water" and body awareness
- Reduced shoulder soreness after training
- Perceived technical improvements in catch and pull phases
- Increased confidence in training

4.8.2 Implementation Challenges
Projected challenges identified by coaches:
- Compliance with supplementary training
- Balance with other training priorities
- Individual variation in flexibility and response
- Timing relative to competition schedule

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