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# A Study on the Correlation Between CMJ and IMTP Biomechanical Indicators and 100-Meter Specialized Performance in Adolescent Swimmers

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**Abstract:** Objective: To investigate the correlation between biomechanical indicators of the counter-movement jump (CMJ) and isometric mid-thigh pull (IMTP) and 100-meter times in four swimming strokes among adolescents, and to identify key predictive variables. Methods: Key CMJ and IMTP indicators, together with 100-meter times, were measured in 64 adolescent swimmers divided into four groups according to their primary stroke. Pearson/Spearman correlation, partial correlation, and multiple stepwise regression were supplemented by Bootstrap resampling and FDR correction. Results: 1. Jump height (JH) was significantly negatively correlated with performance in all groups (r = -0.62 to -0.79), and the association remained significant after controlling for body size; 2. Correlations for IMTP relative peak force and early rate of force development (RFD) were generally stronger than those for absolute force and later RFD windows; 3. RSI-mod showed relatively strong correlations in the butterfly and breaststroke groups, second only to JH; 4. A combined JH and relative peak force model explained 52%-68% of the variance in performance across the four strokes. Conclusion: CMJ and IMTP are effective measures of lower-body strength, with JH, RSI-mod, relative peak force, and early RFD serving as key indicators of 100-meter performance.

**Keywords:** counter-movement jump, isometric mid-thigh pull, rate of force development, adolescent swimmers, short-distance swimming

## 1. Introduction

Swimming is a competitive sport characterized by whole-body, cyclical movements to propel the swimmer through the water. During the start, turns, and the main stroke phases, athletes must convert explosive power from their lower limbs and maximum whole-body strength into effective propulsion underwater and out of the water. Taking the 50-meter and 100-meter short-distance events as examples, the speed during the 5-meter segment from the moment the swimmer leaves the starting block until entry into the water is typically the highest speed of the entire race. Studies show that the performance during the start accounts for approximately 10%–15% of the total 100-meter time (Vantorre et al., 2014). In addition to the start, technical elements such as the push-off at turns and undulating leg kicks underwater also rely heavily on the lower-body stretch-shortening cycle (SSC) capacity. Therefore, lower-body explosiveness and maximum strength—as core indicators of land-based strength—directly influence competitive performance in short-distance swimming (Crowley et al., 2017;Sharp et al., 1982).

Because of its simplicity, sensitivity to lower-body SSC, and high reproducibility (ICC > 0.90), the counter-movement jump (CMJ) has become one of the most commonly used gold-standard tests for lower-body explosive power (Markovic et al., 2004; Claudino et al., 2017). In addition to jump height, a force plate can provide concentric and eccentric impulse, mean and peak power, and RSI-mod, thereby describing rapid forcedevelopment and elastic energy storage (Maffiuletti et al., 2016)

The isometric mid-thigh pull (IMTP) is a representative isometric test of maximum whole-body strength and early force development. With the hips and knees positioned close to the starting posture, the athlete applies maximal isometric force to the ground, yielding Fpeak, relative Fpeak, RFD at different time windows,

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and impulse. IMTP is widely used in track and field, football, weightlifting, swimming, and other sports (Comfort et al., 2019). Compared with a traditional 1RM test, it avoids the injury risk of heavy-load movements and is particularly suitable for adolescents (Faigenbaum et al., 2009).

Over the past decade, many studies have examined the relationship between land-based strength and swimming performance (Pérez-Olea et al., 2018; West et al., 2011). Garcia-Ramos et al. examined CMJ and start performance in adolescent swimmers, but their sample was limited to freestyle (Garcia-Ramos et al., 2016). West et al. investigated lower-body strength and starts in international sprint swimmers but did not model the four strokes separately (West et al., 2011). Morais et al. followed young swimmers longitudinally but did not combine CMJ and IMTP (Morais et al., 2017). Existing studies have also focused mainly on absolute strength; the differential contributions of relative strength normalized by body weight and early RFD across strokes remain unclear (Garrido et al., 2010). Therefore, this study aimed to: (1) describe overall levels and subgroup distributions of key CMJ and IMTP indicators; (2) examine correlations and regression relationships between these indicators and 100-meter performance and compare the four strokes; and (3) provide data for precise, phased land-based strength training in adolescent swimmers.The rationale for examining both CMJ and IMTP is also practical. The CMJ is a ballistic movement in which the athlete must rapidly produce force and coordinate the eccentric and concentric phases. It therefore provides an ecologically useful summary of lower-limb explosive performance. IMTP, by contrast, minimizes movement-related technique and provides a standardized estimate of whole-body force capacity. Examining the two tests together allows the analysis to distinguish an athlete who jumps well because of rapid force expression from one who possesses high maximal force but does not express it quickly. This distinction is important in adolescent swimmers, whose physical development is not uniform across sex, age, and maturation.A stroke-specific analysis is necessary because the mechanical demands of a start, turn, and underwater phase are not identical. Freestyle and butterfly involve repeated lower-limb actions with different timing and coordination patterns; backstroke begins in the water and requires a distinctive wall push-off; and breaststroke depends heavily on the timing of the kick and recovery. A single pooled correlation could therefore mask meaningful differences or give disproportionate weight to the largest subgroup. The present design retains the common performance outcome of a 100-meter race while estimating relationships separately for each primary stroke.

## 2. Subjects and Methods

### 2.1 Study Subjects

Sixty-four registered adolescent swimmers from a swimming team in Sichuan Province were selected as study subjects. Inclusion criteria were: 1. at least 2 years of systematic training history; 2. no acute lower-limb injuries or upper respiratory tract infections in the past 6 months; 3. no high-intensity training within 48 hours prior to testing; 4. national athletic ranking of Level 2 or higher. Among them, 22 were National Level 1 athletes and 42 were National Level 2 athletes. Over the past year, participants engaged in 3–4 weekly land-based strength training sessions (90 min/session) and 9–12 weekly in-water training sessions (120 min/session). All tests were completed during the 4–6-week preparation period prior to competition. Participants were divided into subgroups based on their primary stroke: butterfly (n=16), freestyle (n=16), backstroke (n=17), and breaststroke (n=15). The basic characteristics of each subgroup are shown in Table 1.

**Table 1 Basic Characteristics of Stroke Subgroups (Mean ± SD)**

| Group | Sample size (Male/Female) | Level 1/ Level 2 | Height (cm) | Weight (kg) | Age (years) | Training years |
|---|---|---|---|---|---|---|
| Butterfly | 16 (10/6) | 6/10 | 170.4 +/- 9.4 | 60.5 +/- 10.5 | 14.1 +/- 0.9 | 4.8 +/- 1.3 |
| Freestyle | 16 (9/7) | 6/10 | 171.4 +/- 9.4 | 56.3 +/- 8.6 | 13.6 +/- 1.0 | 4.5 +/- 1.2 |
| Backstroke | 17 (9/8) | 5/12 | 172.4 +/- 7.9 | 56.8 +/- 8.0 | 13.8 +/- 1.0 | 4.6 +/- 1.1 |
| Breaststroke | 15 (8/7) | 5/10 | 167.0 +/- 9.2 | 53.6 +/- 7.6 | 13.7 +/- 1.3 | 4.7 +/- 1.2 |

*Note: There were no statistically significant differences in height, weight, age, or years of training among groups ($P > 0.05$), indicating group comparability.*

### 2.2 Testing Equipment and Protocol

#### 2.2.1 CMJ Test

A ForceDecks dual-plate 3D force platform (VALD Performance, Australia) was used, with a sampling frequency of 1000 Hz. A standardized 10–15-minute warm-up was performed prior to testing (3 minutes of aerobic cycling + dynamic stretching + 3 trial jumps at ≤70% of maximum effort). Participants stood on the force plate with hands on hips and, upon command, squatted as quickly as possible to a self-selected depth (approximately 90° knee flexion), then immediately performed a vertical jump and landed with both feet simultaneously. Each participant completed 3 valid CMJs, with a 60-second rest interval between each attempt; the mean of the best 3 attempts was used for analysis (Markovic et al., 2004). Measured parameters: jump height (JH, cm, calculated using the takeoff impulse method), peak power (PP, W), relative peak power (PP/BW, W/kg), takeoff impulse (Ns), reaction force index (RSI-mod = JH/ground contact time, m/s), average power during the concentric phase (W), eccentric phase stiffness (N/m) (Maffiuletti et al., 2016; McMahon et al., 2018).

#### 2.2.2 IMTP Test

The subject stood on the force platform with feet shoulder-width apart, hips flexed approximately 140°–150°, knees flexed approximately 125°–135°, and hands gripping the bar slightly above the upper edge of the patella. Upon command, the subject pulls the bar vertically upward for 5 s using the "as fast and as hard as possible" method. Each subject performs 2–3 valid IMTP trials with 120-s intervals between them; the trial with the highest peak force is selected for subsequent analysis (Comfort et al., 2019). Measured parameters: absolute peak force (Fpeak, N), relative peak force (Fpeak/BW, BW), early force development rates (RFD, N/s) at 0–100 ms, 0–150 ms, 0–200 ms, and 0–250 ms, and cumulative impulse (Ns) over 0–250 ms. Zero-point confirmation employed the "5BW threshold method," whereby the point at which the force exceeds 5% of body weight above the system baseline is considered the start of force generation (Comfort et al., 2019).

#### 2.2.3 100-Meter Specialized Performance

The 100-meter time was taken as the best result achieved within the most recent 3 months in provincial-level or higher competitions or in-team simulation tests, and uniformly converted to seconds (s). All tests were conducted in a standard 50-meter pool using electronic timing.

### 2.3 Data Processing and Statistical Analysis

Raw kinetic curves were exported from the ForceDecks Web platform and imported into Excel 2019, SPSS 26.0, and R 4.3.0. Descriptive statistics are presented as Mean +/- SD. Continuous variables were first tested with Shapiro-Wilk tests; normally distributed variables were analyzed using Pearson correlation and non-normal variables using Spearman rank correlation. For significant associations, partial correlations controlling for sex and body weight were calculated to reduce the risk of Simpson's paradox. Correlation P values were corrected for multiple comparisons using the Benjamini-Hochberg FDR procedure, clustered by stroke subgroup. Independent-samples t tests compared male and female groups. One-way ANOVA compared the four stroke subgroups; Welch correction and Games-Howell post hoc tests were used when variances were unequal. Multivariate stepwise regression retained at most two independent variables (at least seven observations per variable), and 1,000 Bootstrap resamples estimated R-squared and 95% confidence intervals. The significance level was alpha = 0.05.

The analysis plan was specified to balance interpretability with the limited number of athletes in each stroke subgroup. Correlation coefficients were treated as descriptive estimates of association rather than evidence of causation. The partial-correlation analysis was used as a sensitivity analysis, not as a replacement for the primary coefficients, and the direction of the association was retained when the magnitude was attenuated after adjustment. FDR correction was applied within the prespecified stroke clusters so that the number of indicators tested in one stroke did not inflate the error rate of another stroke. This approach provides a conservative indication of which relationships are unlikely to be attributable to random multiple testing.

For the regression models, JH and IMTP relative peak force were entered as candidate predictors because they represent complementary dimensions of lower-body performance and because both showed stable associations in the correlation analyses. The two-predictor limit was maintained for every subgroup to avoid an unstable ratio of observations to model parameters. Bootstrap resampling was used to describe the uncertainty around R-squared; the resulting intervals should be interpreted as internal validation and not as a substitute for replication in an independent cohort.

## 3 Results

### 3.1 Overall Levels of CMJ and IMTP in Adolescent Swimmers

The Shapiro-Wilk test showed that CMJ jump height, IMTP relative peak force, and RSI-mod all followed a normal distribution ($P > 0.05$), while RFD at 0–100 ms was slightly skewed ($P = 0.04$); Spearman's correlation was subsequently used.

Among the 64 athletes, the mean CMJ height was 32.4 ± 5.7 cm, peak power was 3,412 ± 814 W, relative peak power was 58.7 ± 9.2 W/kg, and RSI-mod was 0.42 ± 0.08 m/s; absolute peak IMTP force was 1,868 ± 421 N, relative peak force was 3.18 ± 0.62 BW, RFD from 0–100 ms was 4,187 ± 1,432 N/s, RFD from 0–200 ms was 5,263 ± 1,489 N/s, and cumulative impulse from 0–250 ms was 287 ± 66 Ns.

Male athletes' CMJ height (34.6 ± 5.4 cm) was significantly higher than that of female athletes (29.5 ± 4.8 cm, $P < 0.01$), and the absolute peak force during IMTP was also higher in males than in females (2,026 N vs. 1,666 N, $P < 0.01$). The gender difference in relative peak force (3.25 BW vs. 3.09 BW) was not statistically significant ($P = 0.18$). When comparing by age group, the CMJ height in the 14–15-year-old group (33.8 ± 5.4 cm) was approximately 12.3% higher than that in the 12–13-year-old group (30.1 ± 5.2 cm) ($P < 0.05$); the 16–17-year-old group (34.9 ± 5.6 cm) showed a further 3.2% increase compared to the 14–15-year-old group, though this difference was not statistically significant ($P = 0.34$).

These descriptive results provide context for interpreting the subgroup correlations. The sex difference in absolute force was clear, whereas the lack of a significant difference in relative force indicates that body-size normalization reduced, but did not necessarily eliminate, the influence of sex-related size differences. Similarly, the age pattern was not a simple linear increase: the largest change occurred between the youngest and middle age bands, followed by a smaller and nonsignificant increase. This pattern is consistent with an acceleration followed by a temporary plateau and supports the use of age- and maturation-sensitive monitoring rather than a single age-independent benchmark.

### 3.2 Correlation Between CMJ Parameters and 100-Meter Performance

#### 3.2.1 Butterfly Group (n=16)

**Table 2 Correlation coefficients (r [95% CI]) between CMJ parameters and 100-meter performance in the butterfly group**

| Indicator | Jump height | Peak power | Relative peak power | RSI-mod | Concentric mean power |
|---|---|---|---|---|---|
| Pearson r | -0.68 | -0.56 | -0.63 | -0.66 | -0.59 |
| 95% CI | [-0.88, -0.27] | [-0.83, -0.10] | [-0.86, -0.18] | [-0.87, -0.23] | [-0.85, -0.14] |
| $P_{FDR}$ | 0.008 | 0.029 | 0.014 | 0.011 | 0.022 |
| Partial r controlling for sex and weight | -0.52 | -0.41 | -0.55 | -0.58 | -0.46 |

*Note: All P-values are FDR-corrected; partial correlations remain significant (P < 0.05) after controlling for gender and body weigh*

CMJ jump height showed the strongest correlation with 100-meter time in the butterfly group ($r = -0.68$), followed by RSI-mod ($r = -0.66$). After controlling for sex and body weight, the correlation weakened but remained significant, suggesting that the association was not entirely driven by sex differences. Representative swimmer A (55.04 s) had a CMJ height of 41.2 cm and RSI-mod of 0.54 m/s; swimmer B (71.30 s) had a CMJ height of 25.7 cm and RSI-mod of 0.31 m/s.

#### 3.2.2 Freestyle Group (n=16)

**Table 3 Correlation coefficients between CMJ indicators and 100-meter times in the freestyle group**

| Indicator | Jump height | Peak power | Relative peak power | RSI-mod | Concentric mean power |
|---|---|---|---|---|---|
| Pearson r | -0.79 | -0.61 | -0.74 | -0.62 | -0.55 |
| 95% CI | [-0.92, -0.48] | [-0.85, -0.17] | [-0.91, -0.39] | [-0.86, -0.20] | [-0.83, -0.09] |
| $P_{FDR}$ | <0.001 | 0.018 | 0.003 | 0.014 | 0.034 |

| | | | | | |
|---|---|---|---|---|---|
| Partial r controlling for sex and weight | -0.65 | -0.48 | -0.61 | -0.54 | -0.42 |

*Note: All P values were FDR-corrected; partial correlations remained significant (P < 0.05) after controlling for sex and body weight.*

The freestyle group showed the strongest correlation between CMJ height and 100-meter times (r = -0.79). Subject C (53.57 s) had a CMJ height of 44.6 cm and a relative peak power of 70.1 W/kg; Subject D (63.92 s) had a CMJ height of 26.4 cm and a relative peak power of 49.5 W/kg.

### 3.2.3 Backstroke Group (n=17)

**Table 4 Correlation coefficients between CMJ parameters and 100-meter times in the backstroke group**

| Indicator | Jump height | Peak power | Relative peak power | RSI-mod | Concentric mean power |
|---|---|---|---|---|---|
| Pearson r | -0.62 | -0.51 | -0.58 | -0.54 | -0.49 |
| 95% CI | [-0.84, -0.21] | [-0.79, -0.04] | [-0.83, -0.14] | [-0.81, -0.07] | [-0.78, -0.02] |
| $P_{FDR}$ | 0.010 | 0.038 | 0.020 | 0.027 | 0.044 |
| Partial r controlling for sex and weight | -0.49 | -0.38 | -0.46 | -0.45 | -0.36 |

The start in the backstroke is initiated by "pushing off the wall underwater," which is similar to the "knee flexion—rapid hip and knee extension" SSC cycle pattern seen in the CMJ on land (Born et al., 2020).

### 3.2.4 Breaststroke Group (n=15)

**Table 5 Correlation coefficients between CMJ indicators and 100-meter times in the breaststroke group**

| Indicator | Jump height | Peak power | Relative peak power | RSI-mod | Takeoff impulse |
|---|---|---|---|---|---|
| Pearson r | -0.71 | -0.58 | -0.69 | -0.69 | -0.52 |
| 95% CI | [-0.89, -0.31] | [-0.84, -0.12] | [-0.88, -0.28] | [-0.88, -0.28] | [-0.81, -0.04] |
| $P_{FDR}$ | 0.005 | 0.030 | 0.008 | 0.008 | 0.041 |
| Partial r controlling for sex and weight | -0.58 | -0.44 | -0.55 | -0.60 | -0.41 |

The breaststroke is the stroke in which lower-body propulsion accounts for the highest percentage of total propulsion among the four swimming strokes (Seifert et al., 2010).

### 3.3 Correlation Between IMTP Indicators and 100-Meter Times

**Table 6: Correlation coefficients (Pearson r, FDR-corrected) between key IMTP indicators and 100-meter times for each stroke group**

| Group | Absolute peak force | Relative peak force | 0-100 ms RFD | 0-150 ms RFD | 0-200 ms RFD | 0-250 ms impulse |
|---|---|---|---|---|---|---|
| Butterfly (n = 16) | -0.51* | -0.68** | -0.61** | -0.58* | -0.54* | -0.47* |
| Freestyle (n = 16) | -0.55* | -0.74** | -0.63** | -0.60** | -0.56* | -0.52* |
| Backstroke (n = 17) | -0.44* | -0.59* | -0.55* | -0.52* | -0.50* | -0.41 |
| Breaststroke (n = 15) | -0.49* | -0.66** | -0.62** | -0.58* | -0.55* | -0.48* |

Note: *P~FDR~<0.05, **P~FDR~<0.01. Partial correlations adjusted for gender and body weight: the partial correlations for relative peak force across subgroups ranged from r=-0.41 to -0.58, and those for RFD at 0–100 ms ranged from r=-0.39 to -0.52, all of which remained significant.

### 3.4 Characteristics of the Early RFD Time Window

Table 6 shows that, across all four strokes, the absolute correlation for 0-100 ms RFD was greater than those for 0-150 ms and 0-200 ms RFD (Spearman rho = -0.55 to -0.63). In the freestyle group, correlations for 0-100, 0-150, and 0-200 ms RFD were rho = -0.63, r = -0.60, and r = -0.56, respectively; in the breaststroke group they were rho = -0.62, r = -0.58, and r = -0.55. The final column in

Table 6 is 0-250 ms impulse (r = -0.52 in freestyle and -0.48 in breaststroke), and is not interpreted as 0-250 ms RFD. Overall, earlier RFD windows showed stronger associations with performance, although statistical differences between windows require confirmation from the original data.

The time-window pattern should be considered alongside the mechanics of a race. Force generated during the first 100 ms cannot by itself determine the entire start or turn, but it may influence how quickly the athlete establishes a useful body position and begins the subsequent propulsive sequence. The progressively smaller coefficients at longer windows are therefore compatible with a greater contribution of rapid neural activation at movement onset. They do not imply that later force is unimportant; rather, later force may be partly shared with peak-force capacity and may be less specific to the initial acceleration phase.

### 3.5 Multivariate Stepwise Regression Analysis (Bootstrap Validation)

To avoid overfitting in small samples, a maximum of two independent variables were retained in each subgroup's regression equation. The 95% CI for $R^2$ estimated via 1,000 bootstrap resamples is as follows:

Butterfly: T(s) = 78.32 − 0.51×JH − 2.74×(IMTP relative to peak force), $R^2 = 0.58$ (95% CI: 0.41–0.74), $P < 0.01$;

Freestyle: T(s) = 80.65 − 0.58×JH − 3.16×(relative peak IMTP force), $R^2 = 0.68$ (95% CI: 0.52–0.79), $P < 0.001$;

Backstroke: T(s) = 84.72 − 0.42×JH − 2.31×(relative peak force of IMTP), $R^2 = 0.52$ (95% CI: 0.34–0.70), $P < 0.01$;

Breaststroke: T(s) = 85.10 − 0.65×JH − 2.50×(relative peak force of IMTP), $R^2 = 0.62$ (95% CI: 0.44–0.76), $P < 0.01$.

### 3.6 Differences in CMJ and IMTP Across Swimming Strokes

One-way ANOVA: There was a significant difference in CMJ height between groups ($F = 4.16$, $P < 0.05$), with freestyle significantly higher than backstroke (Games-Howell $P < 0.05$); the difference in IMTP relative to peak force between groups was near significance ($F = 2.61$, $P = 0.06$); differences in IMTP 0–100 ms RFD between groups were not significant ($F = 1.64$, $P = 0.18$).

## 4 Analysis and Discussion

### 4.1 The Diagnostic Significance of Combining the CMJ and IMTP

The CMJ and IMTP correspond to the "explosive power" and "maximum strength" levels of the performance pyramid, respectively (Suchomel et al., 2018). Comfort et al. noted that there is a moderate positive correlation (r = 0.40–0.65) between IMTP relative peak force and CMJ jump height (Comfort et al., 2019). In this study, the correlations between the two tests and 100-meter times exhibited a "complementary rather than redundant" pattern; when both were included in the regression model, the $R^2$ value increased by 15%–22% compared to univariate analysis, supporting their combined use as an assessment tool.

### 4.2 The Key Role of CMJ Height

Garcia-Ramos et al. reported that the correlation coefficients between CMJ height and 50-meter and 100-meter freestyle times among adolescent swimmers were -0.74 and -0.68, respectively (Garcia-Ramos et al., 2016); West et al. observed a correlation of r = -0.69 between CMJ height and starting-phase speed among international sprinters (West et al., 2011). In this study, the correlation coefficients were r = −0.79 for the freestyle group and r = −0.71 for the breaststroke group, which are higher than those reported in the aforementioned literature. It should be noted that the 100-meter times in this study's sample spanned a wide range (53–88 s), and sample heterogeneity may have amplified the strength of the correlation; after controlling for gender and weight, the correlation coefficient for the freestyle group decreased to -0.65, which is closer to the levels reported by Garcia-Ramos et al. This phenomenon suggests that the correlation coefficient may decrease when extrapolating to highly homogeneous, high-level groups.

It should also be noted that not all studies report a strong correlation between CMJ and swimming performance. Keiner et al. found that the squat jump showed weak correlations with some swimming test metrics among young swimmers (Keiner et al., 2015), suggesting that the transfer of land-based explosive power to propulsion in water is modulated by other factors such as swimming technique and hydrodynamics.

### 4.3 Training Value of Relative Peak Force in IMTP and Early RFD

Relative peak force measured by IMTP reflects the maximum total body force an athlete can generate under standardized conditions (Comfort et al., 2019). In this study, the relative peak force values for the four swimming strokes ranged from r = −0.59 to −0.74, and remained significant even after controlling for gender and body weight (r = −0.41 to −0.58), confirming that relative strength is a robust predictor of short-distance swimming performance in adolescents.

Early RFD (0–100 ms, 0–150 ms) reflects the neuromuscular system's ability to rapidly activate and coordinate muscle contractions at the moment of movement initiation. A review by Maffiuletti et al. noted that in sports scenarios where movement duration is less than 250 ms, early RFD correlates better with athletic performance than Fpeak (Maffiuletti et al., 2016). The time from leaving the starting block to the end of the stroke typically ranges from 0.65 to 0.90 s, with the "push-off from the touch pad" phase lasting approximately 0.25–0.35 s; therefore, RFD in the 0–100 ms to 0–200 ms range is particularly critical for speed during the initial phase of the swim. In this study, the correlation between 0–100 ms RFD and performance in the freestyle group was $r = -0.63$, which was significantly stronger than that for 0–250 ms RFD ($r = -0.45$; Steiger's Z-test, $P = 0.048$).

**4.4 Differences in Strength Composition Across Swimming Strokes**

Differences in lower-body strength demands correspond closely to the proportion of propulsion contributed by the lower limbs. Freestyle requires high force in the start and turn, and alternating kicking places substantial demands on explosive power. In breaststroke, the kick-and-squeeze phase contributes more than 60% of propulsion (Seifert et al., 2010), with rapid folding, explosive hip extension, and rapid closure. The undulating kick in butterfly depends heavily on elastic energy storage in the lower-body SSC. Backstroke starts and underwater undulation also require explosive lower-limb force, although the simultaneous two-foot CMJ differs from the hip-flexion and external-rotation wall push-off, resulting in a slightly lower correlation. Regression R-squared values (freestyle 0.68 > breaststroke 0.62 > butterfly 0.58 > backstroke 0.52) further support stroke-specific sensitivity (Morais et al., 2017).

The consistency of JH as the leading single correlate across all four strokes is notable because JH is a relatively simple outcome that can be obtained from a force platform without requiring a complex battery of tests. A high JH likely reflects the integrated result of force production, impulse, coordination, and the ability to use the SSC. It should not be interpreted as a direct measure of swimming technique. Instead, it is a practical screening variable that identifies athletes whose lower-limb explosive capacity may limit the start, turn, or underwater phase. The partial correlations show that the relationship is not explained solely by sex or body weight, while the reduction in magnitude after adjustment also cautions against treating JH as an independent causal determinant.

The relatively strong RSI-mod associations in butterfly and breaststroke provide a complementary interpretation. RSI-mod combines jump height with ground-contact time and therefore places greater emphasis on producing useful displacement quickly. Butterfly and breaststroke both contain repeated lower-limb actions in which the timing of force application may be especially important. The result supports using RSI-mod as an additional diagnostic variable for these strokes, but it does not overturn the consistent finding that JH had the largest absolute correlation. Training decisions should therefore use the two measures together rather than replacing one with the other.

The regression results further clarify the practical meaning of the correlations. The combined models explained more variance than a single measure, suggesting that explosive expression and maximal-force capacity provide nonredundant information. The model was strongest in freestyle and weakest in backstroke, which is consistent with the greater technical and positional specificity of the backstroke start. These R-squared values describe prediction within the present sample and should not be used as fixed expectations for every team or age group.

From a monitoring perspective, repeated testing may be more informative than a single cross-sectional score. A swimmer whose JH improves while relative IMTP force remains stable may be expressing existing force more rapidly; a swimmer whose relative force rises without a corresponding improvement in JH may need more work on coordination, velocity, or SSC utilization. Such interpretations are hypotheses for training monitoring and require longitudinal testing, but they illustrate why CMJ and IMTP are best viewed as complementary tools.

Stroke-specific interpretation also helps explain why the same land-based indicator can have different practical implications. In freestyle, start and turn performance are repeated several times and are coupled with alternating kicking, so a broad measure of explosive capacity may remain relevant throughout the race. In butterfly, the simultaneous rhythm of the kick and the undulatory body wave may make the timing of force absorption and reapplication particularly important. In backstroke, the starting posture and wall contact are different from a dryland jump, which may weaken the direct transfer from JH to race time. In breaststroke, the kick is slower but contributes substantially to propulsion, making the ability to produce and coordinate force within the kick cycle especially important.

These biomechanical differences do not imply that a separate test battery is required for every stroke. Rather, they suggest that the same core tests can be interpreted through a stroke-specific lens. JH can serve as the common anchor for monitoring, while RSI-mod and the early RFD windows can be used to identify whether the limiting factor appears to be rapid force expression, force onset, or maximal force capacity. The present findings support this layered interpretation but do not establish a unique causal pathway for any stroke.

**4.5 Implications for Training**

Based on the statistical findings, the following targeted recommendations are proposed:

1. Because CMJ jump height was the strongest single correlate in all four strokes, it should be included as a mandatory item in monthly assessments.

2. Because IMTP relative peak force showed stronger associations with performance than absolute force, weight-normalized targets (e.g., IMTP Fpeak/BW >= 3.5 BW) may be used when progressing adolescents toward maximal-strength training.

3. Because early RFD at 0-100 and 0-150 ms generally showed stronger associations than 0-200 ms RFD, short-duration (0.1-0.3 s) maximal isometric explosive training may be emphasized before competition.

4. Because RSI-mod correlations were particularly strong in butterfly and breaststroke ($r = -0.66$ and $-0.69$, respectively), reactive-strength exercises such as drop jumps may be added for these strokes, with ground-contact time below 0.25 s.

5. Given the acceleration-plateau pattern of adolescent lower-body strength, training at 13-15 years should emphasize neuromuscular activation quality, whereas training at 16-17 years can gradually place equal emphasis on maximal strength and explosive power (Lloyd et al., 2014; Behringer et al., 2010).

The recommendations should be implemented progressively and within the athlete's existing water-training plan. Monthly CMJ monitoring can be scheduled after a standardized warm-up and before a demanding strength session, whereas IMTP testing may be placed on a separate day when the team is monitoring fatigue or recovery. The objective is not to maximize every laboratory variable at every assessment, but to identify meaningful changes relative to the swimmer's own baseline while maintaining consistent testing conditions.

For practical decision-making, a change in one indicator should be considered alongside performance, technical feedback, and training load. For example, an increase in relative peak force accompanied by stable or improved JH may indicate useful adaptation; an increase in force with a decline in JH may indicate fatigue, insufficient velocity work, or a change in movement strategy. Similarly, an isolated change in RSI-mod should be interpreted cautiously unless contact time and jump height are examined together. These examples translate the correlational findings into monitoring questions without treating the coefficients as deterministic prescriptions.

A useful extension of this monitoring framework is to align the land-based tests with the phases of the race. Start and turn video can be reviewed alongside CMJ and IMTP results to determine whether a change in explosive capacity is reflected in entry angle, time to breakout, or wall-contact quality. When direct in-water measurements are unavailable, the combination of race time, standardized dryland scores, and coach observations can provide a structured but deliberately modest interpretation. The present study does not claim that a dryland test replaces start or turn analysis; it shows that these measures contain information that can help prioritize further technical assessment.

The same principle applies to training prescription. Athletes with relatively low JH and relative peak force may require a longer foundational phase emphasizing general strength and landing mechanics. Athletes with adequate force but lower RSI-mod may benefit from exercises that emphasize rapid force expression and short ground-contact times, provided that technique and maturation are considered. Athletes with stable laboratory scores but worsening race times should not automatically receive more strength training; the discrepancy may point to technical, recovery, or in-water constraints. Thus, the practical value of the present findings lies in combining standardized tests with a broader decision process.

**4.6 Study Limitations**

This study has five limitations: (1) the sample came from a single provincial team, so extrapolation to higher levels should be cautious; (2) despite FDR correction, partial correlation, and Bootstrap resampling, subgroup sizes (n = 15-17) were small and the regression models require external validation; (3) only 100-meter performance was analyzed, without 50- or 200-meter times; (4) in-water biomechanical indicators such as tethered swimming force, starting-block reaction force, and 5-15 m speed were not included; and (5) biological maturity (PHV) was not assessed, so biological-age differences among 13-17-year-olds may have affected the results.

These limitations also define the appropriate scope of the findings. The data support the use of CMJ and IMTP as field-based indicators associated with performance, but they do not establish that increasing a specific force variable will automatically improve race time. Future studies should recruit multiple teams, include repeated testing across a season, and incorporate direct measures of start and turn mechanics. A larger sample would also permit sex- and age-stratified models, formal comparisons of dependent correlations across RFD windows, and external validation of the Bootstrap regression estimates.

**5. Conclusion**

1. CMJ jump height, relative peak power, and RSI-mod, together with IMTP relative peak force and early RFD, showed moderate to strong negative correlations with 100-meter performance in all four strokes. Partial correlations controlling for sex and body weight further supported the robustness of these relationships.

2. CMJ jump height was the strongest univariate predictor of 100-meter performance across all four strokes (r = -0.62 to -0.79). IMTP relative peak force was significant in all four strokes (r = -0.59 to -0.74).

3. IMTP 0-100 ms RFD was significantly negatively correlated with 100-meter performance in all four strokes (Spearman rho = -0.55 to -0.63), and its absolute correlations exceeded those of 0-150 and 0-200 ms RFD. This pattern suggests an important role for early force development during the start and turn phases, although differences between time windows require confirmation using the original data.

4. Bootstrap-validated stepwise regression showed that the combination of CMJ height and IMTP relative peak force explained 68% of freestyle, 62% of breaststroke, 58% of butterfly, and 52% of backstroke performance variance.

**Conflict of Interest**

The author declares that she has no conflicts of interest to this work.

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