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Biomechanical Analysis of Limb Coordination in Front-Crawl Among Elite S10 and S12 Para Swimmers: Implications for Performance Optimization

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Abstract: Para swimmers categorized as S10 and S12 are of particular interest due to their disability grading being closest to that of able-bodied swimmers, making them an ideal group for investigating disparities in limb coordination patterns. This study aimed to investigate whether S10 and S12 para swimmers, whose disability grading for movement and visual ability, respectively, were the closest to that of able-bodied swimmers, would differ in terms of the biomechanics of limb coordination. This study recruited twenty para swimmers (ten with minor limb absence (S10) in the hand and ten with minor visual impairment (S12)). Using panoramic video, the phase duration, stroke length, stroke rate, index of coordination, synchronization, and inter-limb coordination were digitized and compared in the context of a front-crawl sprinting test. The results showed a significantly different duration of the recovery phase for S10 para swimmers at the affected side, where a more random coordination pattern between arm and leg at the pull and push phases was statistically seen. The variation of the inter-limb coordination gradually increased for S10 para swimmers from hand entry to the end of push, but gradually reduced for S12 para swimmers. These results suggest that the same pace was achieved by different hand–leg coordination patterns according to their physical constraints. Consequently, the unique coordination patterns of different para swimmers from this study offer an opportunity to explore the adaptive strategies and biomechanical adjustments that enable optimal performance for para swimmers.

Keywords: sports biomechanics; inter-limb coordination patterns; para swimming

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1. Introduction

In front-crawl swimming, upper limb movement is divided into four phases: entry and catch (A), pull (B), push (C), and recovery (D), in which pull (B) and push (C) are defined as propulsive phases, and the two other phases are the non-propulsive phases [1]. The inter-limb coordination patterns in swimming could be quantified by continuous relative phase [2], the index of coordination (IdC) [1], the index of synchronization (IdS), and the index of inter-limb coordination (IdIC) [3]. The IdC is based on the proportion of non-propulsive phases between the two arms [4]. The IdC quantifies the time lag between arm propulsive coordination in front-crawl swimming and describes three modes: catch-up (IdC < 0), opposition (IdC = 0), and supposition (IdC > 0) [1]. The propulsive force of front-crawl swimming is generated by the alternating arm movements with a fraction of contribution from the up and down beating of the legs, which also plays a crucial role in maintaining balance and coordination [5,6]. Carmigniani et al. [6] revealed that at low paces, swimmers perform alternating arm strokes with gliding phases in catch-up mode where the IdC remains constant with the increasing speed. When swimming at high paces (above 1.7–1.8 m/s) in the coordination of supposition mode [1,6], the propulsive phase from the arms becomes overlapped, and the gliding phases disappear, resulting in a continuous propulsive process. The arms contribute more propulsion, with 85% of the propulsive force generated by the upper limb movements [7,8].

The continuous relative phase is widely used to quantify the continuous inter-limb or inter-joint coordination; for example, the upper limb movement through changes in limb spatial angles [9,10]. In swimming, the continuous relative phase complements the IdC by providing an instantaneous change in the limb motion that is lacking from the description of swimming coordination from spatial–temporal aspects [11]. A recent study [3] quantified the overall inter-limb coordination between the arm and leg movements beyond the IdC, describing swimming coordination without considering the effect of the kicking behavior. They [3] used the index of synchronization (IdS) to describe the coordination between upper and lower limb movement cycles. The IdS quantifies the degree of synchronization between the upper and lower limbs, with values approaching zero indicating a synchronized mode [3]. Furthermore, this study also utilized the index of inter-limb coordination (IdIC) to analyze the cyclic spatial–temporal relationship between the upper and lower limbs. For instance, Mezêncio et al. [3] classified the upper-limb movement during front-crawl swimming into four distinct stages: catch, pull, push, and recovery. Considering the leg positions during these stages, the IdIC classified each stroke phase into four possible categories: upbeat in-phase, downbeat in-phase, upbeat out-phase, and downbeat out-phase. This categorization enabled a comprehensive analysis of the coordination between the upper and lower limbs, facilitating an assessment of their coordination patterns during swimming performance.

Para swimmer classification is a structured method aimed at ensuring equitable competition for athletes with disabilities [12]. It involves assessing each athlete's impairment and its impact on swimming performance to group competitors into classes with those with similar functional abilities [13]. Notably, inter-limb coordination in swimming is influenced by various factors, including body dimensions [14,15], propulsive force [16,17], passive and active resistance [18], stroke rate [18], and breathing patterns [19]. Furthermore, it is crucial to consider the adaptations in para swimmers, as previous studies have often overlooked the unique challenges and modifications required for disabled swimmers. Understanding these adaptations is essential, as they can significantly impact inter-limb coordination and overall swimming performance. This study on para swimmers not only highlights the complexity of swimming as a skillful movement, but also emphasizes the need for specialized research that addresses the balance between stability and variability in their swimming techniques. Efficient coordination between the upper and lower limbs is vital for overcoming water resistance and propelling the body forward, showcasing the intricacies involved in this demanding sport [20].

More traditional approaches to studying expert performance in swimming have led scientists and coaches to search for a putative 'ideal' inter-limb coordination pattern that would provide a biomechanical profile [21]. However, this approach is challenging when optimizing para swimming movement due to their interpersonal differences. From an ecological dynamics framework perspective, this specific coordination pattern between kick and pull emerged from the interaction of key constraints including the swimming event, environment, and the para swimmer's unique characteristics and capabilities. Para swimmers' unique coordination patterns emerge from self-organization under the influence of physical constraints, indicating the crucial role of these constraints in shaping performance [22]. The variability between swimming strokes suggests that the non-linear characteristics in the coordination patterns, which would be functional to optimize stroke efficiency [23,24], especially for para swimmers who cannot adhere to one optimal movement pattern. Paralympic swimming is also a renowned competitive sport worldwide, and it classifies disabled athletes based on their functional levels and abilities [25]. Physical impairments inevitably affect their inter-limb coordination. Amputee swimmers often adopt an asymmetrical swimming strategy to coordinate their intact arm with the amputated arm. The coordination of the upper limbs in amputee swimmers is influenced by variations in swimming velocity, with the frequency of strokes from the amputated arm playing a critical role in determining overall propulsion. Improving the coordination abilities of disabled athletes holds promise for enhancing their overall performance [26].

The researchers validated the feasibility of using the IdC to measure the swimming performance of individuals with disabilities and the IdIC to measure the hand–leg coordination patterns [2,3]. However, there is a notable absence of research on the inter-limb coordination in swimming for disabled individuals. Swimmers classified as S10 and S12 are of particular interest because their disability grading is closest to that of able-bodied swimmers. This makes them an ideal group for investigating disparities in limb coordination patterns, offering a unique opportunity to explore the adaptive strategies and biomechanical adjustments that enable optimal performance despite physical limitations. An in-depth understanding of the intricacies of limb coordination in these athletes is essential for the development of personalized training interventions and rehabilitation protocols tailored to their unique requirements. Consequently, comparative studies examining the biomechanics of limb coordination between these individuals and their able-bodied counterparts can provide valuable insights into the mechanisms that underpin their exceptional performance capabilities. Therefore, we hypothesized that no general optimal coordination pattern would exist for para swimmers, and the para swimmers with minor amputee impairments (S10) would display higher variability in terms of inter-limb coordination compared to the para swimmers with minor visual impairments (S12).

2. Materials and Methods

2.1. Participants

Twenty male front-crawl para swimmers (S12: 22.12 $\pm$ 2.74 years old, 66.12 $\pm$ 6.89 kg body weight, 175.38 $\pm$ 6.03 cm height; S10: 20.88 $\pm$ 3.86 years old, 61.78 $\pm$ 7.45 kg body weight, 171.12 $\pm$ 6.78 cm height) were recruited from the national para swimming team, as seen in Figure 1. According to the World Para Swimming Classification Rules and Regulations [12,13], the S10 classification was defined as when front-crawl or backstroke swimming movement is affected at a low level in the legs, moderately in the hip joint or feet, to a high degree in one foot, or minor limb absence, but the S10 para swimmers in this study were all minor limb absence below the hand on one side only to control for confounding variables (Figure 1). Their 50 m front-crawl times ranged between 25.7 s and 27.1 s. The S12 para swimmers, by the classification rules [12,13], are defined as those with vision impairment with a visual field of less than 5 degrees radius or a higher visual acuity than no light perception or very low visual acuity. In order to control for confounding variables, all ten S12 para swimmers in this study were further tested to be unable to read the letter on a cell phone positioned 10 cm from their eyes (Figure 1). All ten S12 para swimmers were unable to read the letter on the cell phone with maximal screen brightness. All S12 and S10 participants in this study were finalists in national-level competitions. Their 50 m front-crawl times were between 24.7 s and 26.5 s, with no significant difference between the two groups ($p > 0.05$). All twenty participants were able to complete the testing successfully. However, one participant filmed using an 8-beat kick pattern in the test was excluded, while the other participants used a 6-beat kick during sprinting. Thus, nineteen participants were further studied.

2.2. Preparation

All tests were conducted in a 50 m pool on the same day. Before the formal testing, testers arrived at the pool two hours early to set up the apparatus and equipment. The warm-up was based on their pre-competition routine so that they could perform to their maximum ability. Participants used a push start from the wall and sprinted 50 m at maximal effort by front-crawl. Each participant completed four successful 50 m trials at their 100-pace speed.

2.3. Measurement Procedure

Four high-speed cameras (E2, Z CAM, Shenzhen, China), frame rate: 60 fps, resolution: 1920 $\times$ 1080) were synchronized in the system [27]. One camera was positioned at 20 m by the side of the swimming pool to record the segmental movement above water, and three cameras were placed underwater at distances of 20 m, 25 m, and 30 m from the starting block to capture the clean swimming for 20 m in a 50 m pool. The successive upper-limb movement (i.e., entry and catch (A), pull (B), push (C), and recovery (D)) [1] and lower-limb kicking (i.e., upbeat and downbeat phases) were digitalized. The swimming velocity was set to each participant's 100-pace time using a pace light positioned at the bottom of the pool, ensuring that participants followed the pace light within the recording area. If the researchers found participants failed to follow the pace lights, participants were instructed to repeat the test. Three consecutive stroke cycles for each participant were selected and recorded from 15 to 35 m. The biomechanical data for each side of the participants' stroke were recorded twice during a total of four trials. A rest period of 10 min was provided between trials for each participant.

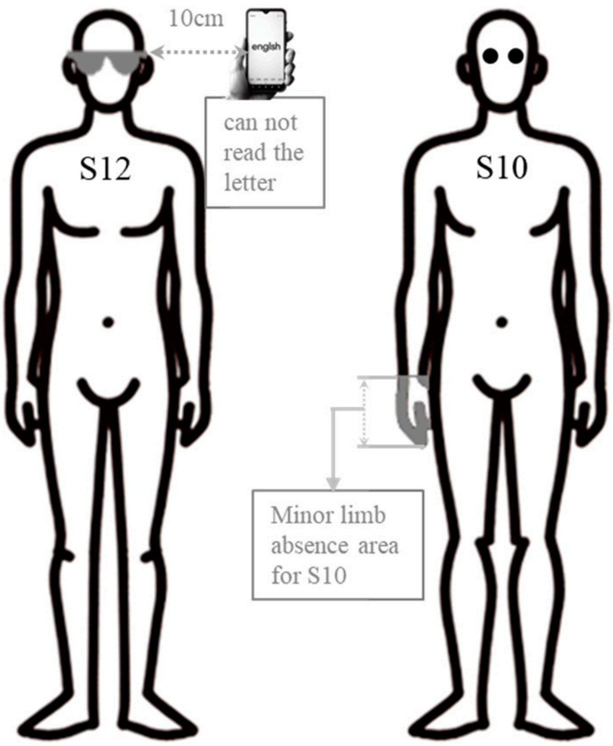

Figure 1. Selection of Participants with Minor Visual Impairment (S12) and Limb Impairment (S10).

2.4. Data Processing

Kinovea was used to digitalize the different phases of upper- and lower-limb movements. The instantaneous kicking position was processed via the Hilbert transform using the method by Mezêncio [3], where NumPy (NumPy v1.21.6) and SciPy (SciPy v1.8.1) were used to transform the vertical position to the phase angle. In a kicking cycle, for example, the foot at the "lowest" position, namely at the end of the downbeat or the beginning of the upbeat, is defined as 0° for the phase angle. When upbeating to the "middle" position (horizontal), the foot position is defined as 90°. Upbeating to the "lowest" position is defined as 180°. When downbeating, the foot passes the "middle" position again, defined as 270°. Finally, as the foot continues downbeating to its "lowest" position again, it is defined as the end of this cycle with a phase angle of 360°, or 0°, considered as the beginning of the next kick cycle. Thus, a complete kick cycle can be transformed into a continuous time series curve characterizing the continuous lower-limb movement using phase angle. As arm movement is on the same time series, the stroke cycle can be positioned to its relative foot position [28]. During the successive arm stroke phase, phase A is defined as entry and catch phase (from the hand's entry into the water to the beginning of its backwards movement); phase B is defined as the pull phase (from the beginning of the hand's backwards movement to the hand's arrival in the vertical plane to the shoulder); phase C is defined as the push phase (from the hand's position below the shoulder to its release from the water); and phase D is defined as the recovery phase (from the hand's release from the water to its following entry into the water) [1].

The index of coordination (IdC) [1,6] is the proportion of non-propulsion phase (lag time) between two consecutive strokes (two arms) over a swimming cycle time (T).

The lag time is calculated:

$$\text{Lag time} = t^{i}_{end} - t^{i+1}_{start} \tag{1}$$

where i represents the ith stroke, so $i + 1$ means the next stroke on the other side arm; t_{start} represents the chronological time point of the start of the propulsive phase (phase B); and t_{end} represents the end of the propulsive phase (phase D, i.e., the beginning of the recovery phase), measured in the underwater video respectively.

$$\text{IdC} = \frac{t^{i}_{end} - t^{i+1}_{start}}{T} \tag{2}$$

IdC (Equation (2)), according its value, can be defined as three modes [1]: IdC < 0 means catch-up mode, where the lag time is negative; IdC = 0, i.e., opposition mode, where the lag time is zero; and IdC > 0, i.e., superposition, where the lag time is overlapped because the start of next propulsive phase (t^{i+1}_{start}) on other side is earlier than the end of current propulsive phase (t^{i}_{end}). The index of synchronization (IdS) assesses coordination between the upper and lower limbs in swimming [3]. It calculates the phase shift between stroke phases and kick phase (Equation (3)):

$$\text{IdS} = \frac{[(KR + 0.5SR) mod SR]}{SR} - 0.5 \tag{3}$$

where KR is the kicking rate and SR is the stroke rate. The numerical value of IdS ranges from -0.5 to 0.5, and IdS values within ±0.1 are considered the synchronized coordination mode. In contrast, the values closer to ±0.5 suggest inconsistent coordination mode, where a large phase shift happens between the stoke and kick phases according to the equation. The index of inter-limb coordination (IdIC) is used to assess the coordination between the upper and lower limbs [3]. A set of IdIC values for one stroke cycle composed of four key data points (A, B, C, and D) corresponding to the beginning time point of four phases in a stroke (catch, pull, push, and recovery) [3], which are the foot position during kicking quantified by the angle ranged from 0–360° in order to term the relative phase between the upper- and lower-limbs. An example of IdIC data for a S12 swimmer's stroke on the left side coordinated with the right leg is shown in Figure 2.

The index of inter-limb coordination (IdIC) [3], which is calculated as the relative foot position during successive arm stroke phases, was divided into four coordination patterns (Table 1). The coordination pattern between the upper- and lower-limbs could be categorized into four types: (i) upbeat in-phase, where the foot initiates the upbeat (foot phase between 360° (0°) and 30° e.g., Figure 2a or between 150° and 180°) simultaneously with the start of the related stroke phase of their arms (i.e., phase A/B/C/D); (ii) downbeat in-phase, where the foot downbeats (foot phase angle between 330° and 360° (e.g., Figure 2b) or between 180° and 210° e.g., Figure 2e) in sync with the start of the related stroke phase; (iii) upbeat out-phase, where the foot makes an upbeating motion when the related stroke phase begins (foot phase between 30° and 150°, e.g., Figure 2c); and (iv) downbeat out-phase, where the foot downbeats when the related stroke phase begins (foot phase between 210° and 330°, e.g., Figure 2d). A lag of ±30° [2,3] was accepted in this study for the determination of a coordination mode. Therefore, an in-phase mode was assumed to occur for 330° < phase angle < 30° and 150° < phase angle < 210°, while the out-phase mode was taken to be between 30° < phase angle < 150° and 210° < phase angle < 330°.

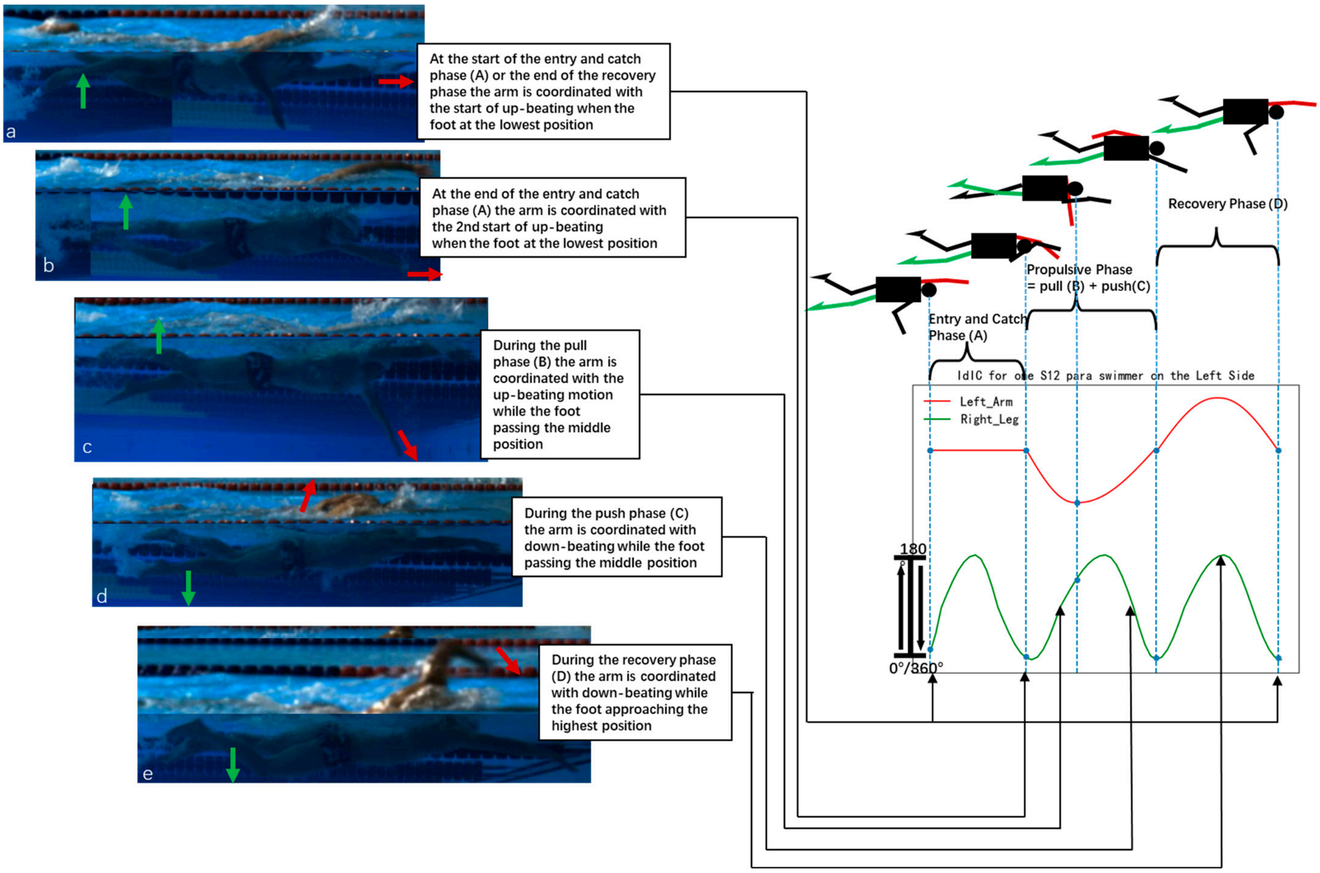

Figure 2. The four stroke phases of a typical S12 para swimmer's left arm (red arrow and curve) coordinate with the right leg kicking behavior represented by the green arrow and curve. The screenshots, labelled a, b, c, d, and e, showcase the swimmer's foot position during different phases. The lowest foot position with a 0° phase angle is shown in the screenshots α and β. The screenshots γ and δ exhibit the upbeating and downbeating passing through the middle position, with 90° and 270° phase angles, respectively. The screenshot ε displays the highest foot position with a 180° phase angle.

Table 1. The index of inter-limb coordination definition chart according to the relative foot position.

The Relative Foot Position	Relative Phase Between Foot and Arm	IdIC
330° < phase angle < 360° (0°)	In-phase	In-phase Downbeat
0° < phase angle < 30°		In-phase Upbeat
30° < phase angle < 150°	Out-phase	Out-phase Upbeat
150° < phase angle < 180°	In-phase	In-phase Upbeat
180° < phase angle < 210°		In-phase Downbeat
210° < phase angle < 330°	Out-phase	Out-phase Downbeat

2.5. Statistical Analysis

The normality of the kinematic data was analyzed using the Shapiro–Wilk test. All kinematic data were presented as mean ± standard deviation (SD). The durations of phases A, B, C, and D were compared between left and right side strokes using a paired T-test among the same group (SciPy v 1.8.1). An independent T-test (SciPy v 1.8.1) was employed to compare the differences in phase duration, distance per stroke (DPS), stroke rate (SR), IdC and swimming speed (DPS × SR) between S12 and S10 para swimmers for each side.

The chi-square test was used to determine if there was a uniform random distribution of the kicking phase [3] (i.e., in-phase upbeat, in-phase downbeat, out-phase upbeat, and out-phase downbeat). The 'chi-square' package in R studio (v 3.4.3) was used to calculate the moment-corrected standardized residual for the chi-square test, determining which phase deviated from the hypothetical occurrence of a uniform distribution.

3. Results

Among the basic biomechanical stroke kinematics (Table 2), the duration of phase D (the recovery phase), SR, and DPS between the S10 and S12 para swimmers showed significant differences ($p < 0.01$) from the independent T-test. The durations of phase A and phase D for S10 para swimmers also exhibited significant differences ($p < 0.05$) between the affected and unaffected sides within the group, as determined by the paired *t*-test. However, no significant differences were observed in the IdC and the mean cycle speed, calculated from stroke rate (SR) times and distance per stroke (DPS), between the different sides and groups.

Table 2. Basic biomechanical stroke kinematics for S10 and S12 para swimmers on each side.

	Phase A (s)	Phase B (s)	Phase C (s)	Phase D (s)	IdC $^{\#}$	SR (cycle/min)	DPS (m)	Speed (m/s)
S10 affected side	0.32 ^{a*} ± 0.07 (27%)	0.17 ± 0.03 (15%)	0.28 ± 0.06 (25%)	0.35 ^{a*} ± 0.07 (33%)	0.05 ± 0.06	53.45 ^{l**,r**} ± 2.40	1.94 ^{l**,r**} ± 0.03	1.72 ± 0.09
S10 unaffected side	0.38 ^{a*,l*} ± 0.10 (35%)	0.18 ± 0.03 (16%)	0.26 ± 0.04 (23%)	0.29 ^{a*,l**,r**} ± 0.07 (26%)	0.03 ± 0.05	53.64 ^{l**,r**} ± 1.70	2.00 ± 0.12	1.78 ± 0.11
S12 left side	0.29 ^{u*} ± 0.09 s (28%)	0.14 ± 0.03 s (14%)	0.24 ± 0.05 (23%)	0.36 ^{u**} ± 0.13 (35%)	0.04 ± 0.04	49.20 ^{f**,u**} ± 1.07	2.09 ^{f**} ± 0.10	1.71 ± 0.08
S12 right side	0.34 ± 0.06 (31%)	0.15 ± 0.03 (14%)	0.24 ± 0.04 (22%)	0.36 ^{u**} ± 0.08 (33%)	0.02 ± 0.06	48.93 ^{f**,u**} ± 1.67	2.18 ^{f**} ± 0.19	1.78 ± 0.14

Notes: $^{\#}$ The IdC was calculated for each side [6]. ^{a} The significant difference between two sides in the same group (S10 or S12) from the paired *t*-test. ^{l} The significant difference in comparison to the left side of S12 para swimmers. ^{r} The significant difference in comparison to the right side of S12 para swimmers. ^{f} The significant difference in comparison to the affected side of S10 para swimmers. ^{u} The significant difference in comparison to the unaffected side of S10 para swimmers. * $p < 0.05$, ** $p < 0.01$.

All subjects showed synchronized coordination patterns between the upper and lower limbs, although one 8-beat subject was excluded. The indices of synchronization (IdS) for both groups were distributed between −0.1 to 0.1 (Figure 3); the IdS for both groups were significantly different from the uniform random distribution ($p < 0.01$). Moreover, the chi-square test showed significant differences ($p < 0.01$) in the IdS distribution between S10 and S12 para swimmers. The S10 para swimmers showed the tendency to be more non-synchronized compared to S12 para swimmers, where the IdS for the S10 para swimmers tended to distribute at the margins of the synchronized boundary (i.e., around −0.1 and 0.1). The IdS for the S12 para swimmers showed a more centered distribution, with all the IdS for the S12 para swimmers was within the range between −0.075 and 0.075, while 60% for the S10 para swimmers was inside this range.

The IdIC revealed the specific coordination between the upper and lower limbs in this study. Nineteen athletes adopted a synchronized coordination pattern with six beats per cycle. Their mean inter-limb coordination mode on both sides (ten S10 and nine S12 para swimmers) are displayed separately in Figure 4 ((a) S10 affected side, (b) S10 unaffected side, (c) S12 left side, (d) S12 right side). The S10 and S12 para swimmers started entry and catch (phase A) when their foot positions were in different phases. The S10 para swimmers initiated kick at the start of phase A from the out-phase downbeat phase on average (i.e., foot initiated from an elevated position 236.5° for the mean affected side and 203.6° for the mean unaffected side at phase A). In contrast, the S12 para swimmers initiated upbeat from the lower position, 37.5° (out-phase) and 0° (in-phase), for the mean left and right, respectively. The duration of the entry and catch phase (phase A) took up around one kick cycle on both sides for both groups. The duration of the propulsive phase (pull, i.e., phase B, and push, i.e., phase C) and the recovery phase (phase D) for both groups were in relation to the second and third kick cycles, respectively. Furthermore, the duration of the pull phase (phase B) for the S10 para swimmers matched the first half of the second kick cycle (fully covering the downbeat of the second kick cycle) in both unaffected and affected sides. Still, for the S12 para swimmers, it was less than the first half kick cycle of the second kick cycle at the pull phase (phase B). As for the variation in the IdIC within the group, the S12 para swimmers showed a progressively reduced standard deviation from phase A to D on both sides (from 52.5° to 20.3° on the left, and from 89.9° to 18.8° on the right side), while the S10 para swimmers on both sides showed an increased standard deviation in the IdIC from entry (phase A) to recovery (phase D) in a stroke cycle (from 11.0° to 54.3° on the affected and from 36.5° to 69.6° on the unaffected side), in which the highest and second highest variation in IdIC at phases B and C on the affected side for S10 para swimmers were 87.3° and 102.9°, more than twice compared to the corresponding phase on the affected side (35.4° for phase B and 49.8° for phase C) and both sides for S12 para swimmers (on average, 33.0° for phase B and 25.9° for phase C). The distribution of the IdIC (in Table 3) at phase B and C for S10 para swimmers on the affected side was also the most uniform among all four kicking coordination patterns (i.e., in-phase upbeat (28.57%), in-phase downbeat (14.29%), out-phase upbeat (28.57%) and out-phase downbeat (28.57%)) regarding the arm phase in all groups.

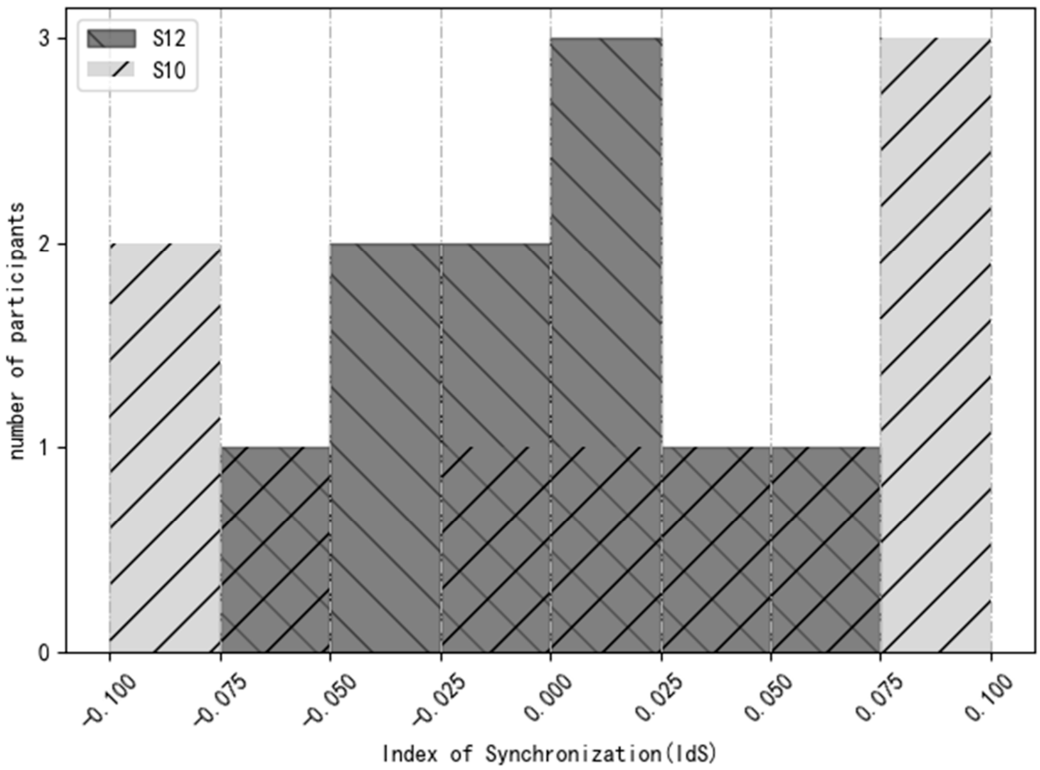

Figure 3. Histograms of the index of synchronization (IdS) within the range of synchronization ($-0.1 \leq \text{IdS} \leq 0.1$) during the sprinting swimming cycle for the S10 and S12 para swimmers.

The index of inter-limb coordination data (IdIC) for each participant was summarized and presented as percentage for each stroke phase (from phase A to D) and kick (i.e., upbeat and downbeat) phases for each group on both sides in Table 3. The "0" at a specific stroke phase meant no corresponding kicking phase at the beginning of the stroke phase. The result of the chi-square test showed that all S10 participants on the affected and unaffected sides at the beginning of stroke phase A were downbeating either in-phase or out-phase with hand entry (phase A). The difference between the affected and unaffected sides for S10 para swimmers mainly occurred during the B, C and D phases. The most uniform random distribution of kicking patterns was seen in phases B and C on the affected side in S10 para swimmers, where phases B and C showed no significant difference from the uniform random distribution by the chi-square test. On the unaffected side of S10 para swimmers, the kicking pattern in phases B and C also obeyed uniform random distribution according to the chi-square test. However, phases B and C seemed more converged than the affected side on the downbeat (75% from 41.67% in-phase and 33.33% out-phase) and upbeat (66.66% from 33.33% in-phase and 33.33% out-phase), respectively.

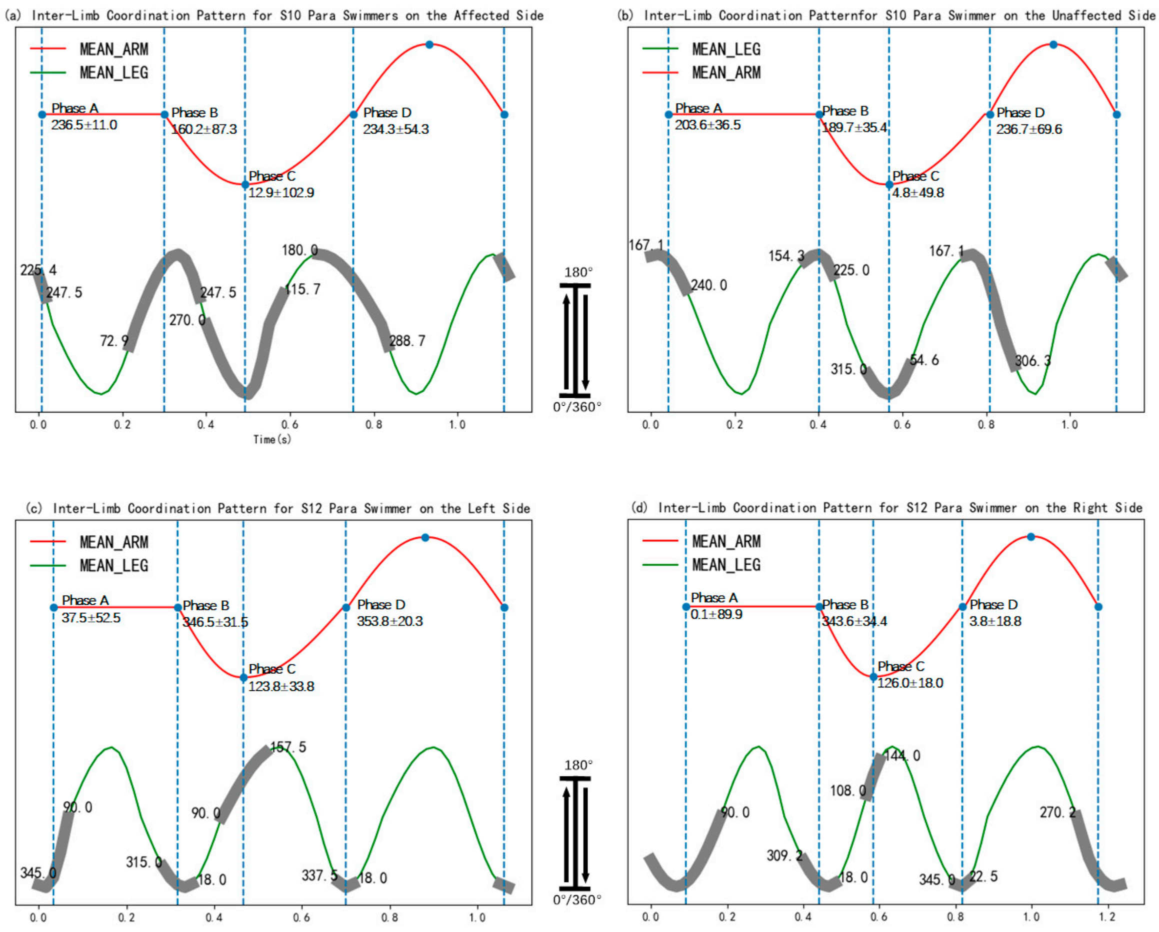

Figure 4. Schematic representation of the index of inter limb coordination (IdIC) for S10 ((**a**) and (**b**) are affected and unaffected sides, respectively) and S12 ((**c**) and (**d**) are left and right sides, respectively) para swimmers. The red curve represents the stroke phase according to the cycle time: A for the entry and catch phase, B for the pull phase, C for the push phase, and D for the recovery phase. The green curve represents the vertical position of the foot corresponding to the same time domain. The gray area represents the variation from different participants in the same group. The mean IdIC for each stroke phase with standard deviation is presented after each phase.

As for S12 para swimmers, during phase A, the occurrence rate of the out-phase kicking pattern on the left side, summing up the upbeat and downbeat, was 46.15%, whereas on the right side, it was 84.62% in total, The occurrence rate of upbeat kicking patterns, including the in-phase and out-phase on both sides at the beginning of push (phase C) and recovery (phase D), was 76.92% and 92.30%, where the converge of the upbeat kicking pattern at stroke phase D showed a significant difference ($p < 0.01$) from the uniform distribution of kick phases on both sides, which demonstrated the symmetric inter-limb coordination of upbeat kicking behavior. Unlike the S10 group, the IdIC in Table 3 for S12 para swimmers presented more significant discrepancies on the left and right sides during the entry and catch phase (phase A) while still preserving a certain degree of coordination consistency in the subsequent phases. Specifically, the kicking patterns converged at the in-phase upbeating phase (0°) at the beginning of stroke phase D with a significant difference from the uniform distribution ($p < 0.01$).

Table 3. The distribution of the IdIC (index of inter-limb coordination) for the S10 and S12 para swimmers on each side, presented as a percentage for the entry and catch phase (A), pull phase (B), push phase (C), and recovery phase (D).

Groups	Phase	In-Phase		Out-Phase	
		Upbeat	Downbeat	Upbeat	Downbeat
S10—affected-side	Phase A **	0 (0.03)	42.86 (0.01)	0 (0.01)	57.14 (0.02)
	Phase B	28.57	14.29	28.57	28.57
	Phase C	28.57	14.29	28.57	28.57
	Phase D	14.29	28.57	14.28	42.86
S10—unaffected-side	Phase A **	0 (0.03)	66.67 (0.009)	0 (0.01)	33.33 (0.3)
	Phase B	0	41.67	25	33.33
	Phase C	33.33	0	33.33	33.33
	Phase D **	25 (0.009)	50 (0.009)	0 (0.01)	25 (0.06)
S12—left	Phase A	53.85	0	46.15	0
	Phase B *	69.23 (0.009)	0 (0.03)	15.38 (0.04)	15.38 (0.04)
	Phase C	7.69	23.07	69.23	0
	Phase D **	76.92 (0.006)	0 (0.03)	15.38 (0.04)	7.70 (0.04)
S12—right	Phase A	7.69	7.69	30.77	53.85
	Phase B *	53.85 (0.008)	0 (0.03)	0	46.15
	Phase C *	0 (0.03)	23.08 (0.02)	76.92 (0.008)	0 (0.01)
	Phase D **	76.92 (0.006)	0 (0.03)	15.38 (0.04)	7.70 (0.04)

Notes: The numbers in the table are occurrence-based percentages of certain IdIC among the corresponding side of the group. The values shown in the brackets represent the moment-corrected p-value, while the chi-square test showed a significant difference; * and ** show the significant levels 0.05 and 0.01 from the chi-square test.

4. Discussion

4.1. The Effect of Timing in Each Stroke Phase

The significant differences in stroke rate and DPS on the affected side were observed between different groups ($p < 0.01$) and are shown in Table 2. Furthermore, a significant difference was observed in the duration of phase D, not only between S10 and S12 para swimmers ($p < 0.01$) but also between the affected and unaffected sides with the S10 para swimmer group ($p < 0.05$). This significant difference between the affected and unaffected sides was also seen in phase A ($p < 0.05$). Compared to the unaffected side, the entry and catch phase (phase A) on the affected side for S10 para swimmers constituted a lower proportion of the total non-propulsive phase, namely a higher proportion in the recovery phase (phase D). On the affected side, S10 para swimmers spent 42% of cycle time on the catch phase and pull phase (phases A + D), lower than that on the unaffected side at 49%. Similar results were reported by Chollet et al. [29], who found that for athletes with asymmetric strength, the ratio of the catch and pull phases on the dominant side was 51.7%, higher than the non-dominant side at 48.4%. This might imply that the disparity in strength arising from arm disabilities can exert an impact on the phase timing between left and right sides, predominantly influencing phases A and D. In this study, the affected side for S10 participants was the lack of a distal end of the upper limb (hand), which might feel weak to sense the flow of water and more challenging to find the 'still water' [30] for them to set up the preloading condition with the extended shoulder blade and the high elbow position before entering an efficient propulsive phase at the end of the catch phase (phase A). This inevitable diminished propulsive deficiency attributable to the absence of the distal segment is regarded as a physical constraint, which might enable S10 para swimmers to adopt a constraint-led approach that entails a decreased time allocation on catch (phase A) but an enhanced time investment on the propulsive phase and recovery phase, thereby accounting for the substantial difference in phase D between S12 para swimmers ($p < 0.01$), as well as between the affected and unaffected side in S10 para swimmers ($p < 0.05$) in Table 2.

During phase D, a straighter elbow movement on the affected side for S10 para swimmers was observed compared to the unaffected side, which might increase the recovery time from the overwater camera. This asymmetric arm recovery movement may counteract the shortened duration of the catch phase (phase A on the affected side in Table 2), equalizing the proportion of the non-propulsive and propulsive phases for both sides in a stroke cycle. The balanced non-propulsive time (phases A and D) between the affected and unaffected sides for S10 para swimmers could potentially contribute to higher stroke efficiency [1]. This is due to the fact that a bilaterally balanced stroke cycle would theoretically enhance stroke efficiency compared to asymmetric strokes [31–33]. The adaptation of increased phase D on the affected side adjusted the asymmetric percentage of non-propulsive phase to balanced, thereby resulting in a balanced propulsive phase. The propulsive phase is the source of the body roll in the water during front-crawl. Barber [32] proposed that an economical stroke achieved through efficient bilateral body roll could reduce drag force while increasing propulsion. However, the imbalance leads to intra-cycle velocity variations, raising the energy cost for the same average speed [34] and deteriorating body postures by maximizing hydrodynamic drag [35]. Although some imbalance in inter-arm coordination (e.g., the hybrid mode: catch-up on one side (IdC < 0) and superstition or opposition on the other side (IdC ≥ 0) is commonly witnessed in short to mid-distance front-crawl swimming, such as used by Michael Phelps, Caeleb Dressel, and Pan Zhanle, and even some mid to long-distance swimmers like Sun Yang during the sprint before finishing, where speed takes precedence over swimming efficiency). Morouço et al. [8] investigated the front-crawl under tethered maximal swimming and quantified the functional imbalance pattern between the upper limbs. They acknowledged that the one-dominant stroke pattern, where the dominant arm provides propulsion, and the other arm is for control and support [36], may result in a deviation from the balanced stroke pattern over time. Many researchers suggested that handedness might influence the force and coordination symmetry in swimming [35,37–39]. Regarding para swimmers, Osborough reported the distinction between the affected and unaffected arms during front-crawl sprinting, where a more catch-up coordination code was observed on the affected side's upper limb. Nevertheless, they also anticipated that the stable repetition of the overall arm stroke cycle is maintained by the propulsion generated from the unaffected arm and the control of inter-arm asymmetry from the affected arm [26]. In our study, although the handedness of S10 para swimmers naturally lay on the unaffected side, the results among upper-limb kinematics, including IdC, SR, DPS, and swimming speed, demonstrated no significant asymmetry (as shown in Table 2) between the affected and unaffected sides. The reason may be the asymmetry stroke mode with high intra-speed variations might not be energy-efficient enough for them to complete the entire race without reducing speed due to their inevitable deficiency and large speed fluctuations [31]. Therefore, the reason for the longer recovery time on the affected side is likely the wait for the completion of the propulsive phase on the unaffected side to fully utilize the propulsive phase at a more streamlined body position, compensating for the inefficiency resulting from the lack of the distal end segment.

4.2. Adaptation of IdIC Due to Hand Disability and Visual Impairment

When using the IdS to analyze S10 and S12 para swimmers, we found that all participants displayed synchronized inter-limb coordination patterns. Meanwhile, Mezêncio et al. discovered that 65% of professional swimmers use synchronous limb movements, and 95% of amateur swimmers use asynchronous limb movements [3]. Similar to the study by Mezêncio [3], we discovered that the IdS effectively distinguishes the non-synchronized and synchronized movements between the upper- and lower-limb for para swimmers. However, when analyzing individuals with high swimming proficiency who can maintain good upper and lower limb synchrony despite differences in disability severity and affected body parts, the IdS alone fails to offer adequate information to elucidate how body disabilities affect the coordination of upper and lower limbs. Using the IdIC, the synchronized coordination pattern was further analyzed between different groups. The visualization of the IdIC (Figure 4) showed that limb disability (S10 para swimmers) had a more significant impact on the variation in the IdIC (gray curve under stroke phase A, B, C, and D in Figure 4) than visual impairment (S12 para swimmers, Figure 4c,d), particularly during stroke phases B and C on the affected side (S10 para swimmers, Figure 4a). In these phases, the diverged distribution of the kicking behavior showed no significant difference from the uniform random distribution in Table 3.

Conversely, the IdIC tended to converge at a particular phase on the unaffected side of S10 para swimmers and on both sides of S12 para swimmers. For example, for S12 para swimmers, both sides at the start (phase B) and end (phase D, i.e., start of the recovery) of the propulsive phase tend to converge at in-phase kicking patterns ($p < 0.01$).

All swimmers adopted a pattern of one arm stroke corresponding to three leg kicks in cycles in Figure 4. However, the data revealed differences in the three continuous kicks in a pull cycle between S10 and S12 para swimmers. In our study, the kicking curve (green curve in Figure 4a) for the affected side of S10 para swimmers displayed significantly more variation at the beginning of the stroke phases compared to the kicking curve of expert swimmers with zero IdS, as previously examined by Mezêncio [3]. Similar to the study by Mezêncio [3], S12 para swimmers in this study showed the three repetitive kicking cycles within a stroke cycle, while the curve shape of the three kick cycles on the affected side of S10 para swimmers in a stroke cycle showed an adapted form (a new attractor) where the shorter duration was seen at the second upbeat phase cycle and longer consequent downbeat phase at the third cycle, as shown in in Figure 4a. These findings suggested that the adapted kicking curve within a pull cycle provided evidence that the S10 swimmers tried to coordinate their kicking to a particular relative phase corresponding to their stroke phases. However, they still displayed higher variation at stroke phases B, C, and D, and showed more random distribution in all four kicking phases.

The hand disability in the S10 para swimmer group probably affected the symmetry (or balance) between the left and right sides. S10 para swimmers, on the affected side, showed a more random distribution of the kicking phases (between in- and out-phase) and directions (between up and downbeat) according to the result of the chi-square test in Table 3. However, the kicking curve in Figure 4a reveals that the shape between the three kicks within a stroke cycle is not perfectly paired compared to the unaffected side. The kicking curve for the affected side (Figure 4a) exhibited a higher rate of angle development in the second upbeat and a consecutive lower rate of angle development at the third downbeat. This shortened upbeat phase probably constructed the consecutive, more prolonged downbeat phase. The longer downbeat phase in Figure 4a may help compensate for the extended non-propulsive phase D on the affected side. This is because the downbeat phase is more propulsive than the upbeat phase, as noted in previous studies [3,40]. The kicking cycles within a stroke cycle suggest that on the affected side, the S10 para swimmers aim to coordinate their kicking rather than executing three consecutive kicks randomly. This structured kicking may enhance balance and propulsive efficiency during the strokes on the unaffected side. Additionally, research on post-stroke gait [41–43] indicates that the unaffected side often engages in support and balance tasks to compensate for the initially impaired affected side. This compensatory behavior can result in asymmetric kinematics during gait.

Malone et al. [44] reported that visual cues aid in timing and coordinating various body parts during movement. In swimming, visual impairments can affect a swimmer’s ability to monitor rhythm [45], which may be the reason for the higher variation in the IdIC seen at the start of the stroke phase. S12 para swimmers with visual impairments struggle to accurately perceive their external environment through visual cues, probably leading to orientation challenges during the initial water entry at phase A. To overcome the drawback to visual feedback, S12 para swimmers may depend on alternative sensory cues, such as proprioception, the impact sensation of water flow on the skin, and auditory input from the water nearby, to acquire information regarding their body positioning and movement [46]. Therefore, once in the propulsive phase, a decreasing trend in the standard deviation of the IdIC for S12 para swimmers was observed. On both sides for S12 para swimmers, the slightest deviations were disclosed at the end of a propulsive phase (phase C), when they could fully sense the drag force from the water to acquire information regarding their body positioning and movement. Moreover, the foot ascendant and descendent movements at the end of the push, i.e., propulsive phase (phase C), in S12 para swimmers were converged in the in-phase coordination pattern with arm movement on both left and right sides (Figure 4c,d), where the foot was at the lowest position, about to upbeat.

4.3. Limitations

Several methodological limitations exist in this study. First, the comparatively restricted sample size does not provide sufficient grounds for drawing general conclusions from the results, although the result showed the normal distribution, suggesting that future research should strive to include a larger cohort of athletes. Furthermore, since we only included male participants, the findings and conclusions of this study are not applicable to female participants. Second, the coordination pattern for S10 and S12 para swimmers could be affected by inter-individual variability. Para swimmers within the same classification (such as S10 and S12) may have varying degrees of impairment, physical attributes, and training backgrounds, which may potentially mask true differences in coordination patterns that exist among athletes. However, to mitigate this issue, we ensured that all participants were from the same national team and trained under the same coach, thus standardizing the training environment. Additional screening criteria were also applied (refer to Figure 1) to further reduce inter-individual variability. Third, the effect of fatigue may affect the coordination patterns, although the rest provided was more than allocated in normal training. While extended rest periods are typically assumed to alleviate the negative impacts of fatigue, the residual fatigue effects from repetitive sprinting test could still compromise coordination patterns during subsequent high-intensity efforts, which may yield a shift from a powerful catch to slippery catch when approaching the propulsive phase.

4.4. Practical Implications

The findings from this study on S10 and S12 para swimmers highlight the importance of developing personalized and adaptive training strategies that cater to individual physical constraints. By acknowledging the unique challenges and opportunities presented by physical and visual impairments, para swimmers can optimize their performance.

There are significant implications for recovery times in stroke phases, particularly for athletes with arm disabilities. The observed differences in phase timing, especially during the catch (phase A) and recovery (phase D) between affected and unaffected sides indicate that strength imbalances can significantly impact performance. By implementing training strategies that promote balanced stroke mechanics and address the asymmetries in arm movement, athletes can potentially improve their overall stroke efficiency. Furthermore, understanding the impact of physical constraints, such as the absence of distal segments, can guide tailored drills that emphasize proper body positioning and arm coordination. This approach can optimize propulsion and recovery times, ultimately leading to better performance in the water. Coaches and athletes should prioritize adjustments in technique and training regimens to mitigate the effects of asymmetry and enhance overall swimming efficiency.

The findings also highlight the importance of understanding coordination adaptations in para swimmers, specifically those with hand disabilities and visual impairments. Coaches and athletes can leverage these insights to tailor training regimens that focus on improving limb coordination and synchrony. In particular, the observed differences in kicking patterns between affected and unaffected sides suggest that targeted drills can enhance balance and symmetry in stroke execution. By recognizing the unique kicking curves and variations among swimmers, coaches can design exercises that accommodate individual disabilities, promoting more effective propulsion and overall performance. Ultimately, these adaptations not only aid in optimizing techniques, but also foster efficiency in athletes as they navigate their specific challenges in the water.

5. Conclusions

The time differences between the affected and unaffected sides during the catch and recovery phases may represent a constraint-led approach by S10 para swimmers to counteract the inevitable reduction in propulsive ability due to the physical constraints of minor limb absence. The IdIC for S12 para swimmers on both sides demonstrated progressively reduced variability from the entry to the recovery phase. In contrast, the IdIC for S10 para swimmers on both sides showed an increased variability within a stroke cycle. Furthermore, the impact of limb disability on the affected side on the variability of the IdIC was more significant than that of visual impairment, particularly during the pull and push phases. However, the adapted kicking pattern for S10 para swimmers validated their ability to coordinate their kicking to a specific relative phase, which may pay off in terms of balance and propulsive efficiency between strokes. The distribution of the kicking phase at most stroke phases was statistically more than the uniform random distribution for para swimmers. Functionally beneficial, task-oriented unique coordination patterns result in differences in IdIC, enabling para swimmers with visual and physical disabilities, who are closest to able-bodied athletes, to achieve the same swimming speed by reorganizing their degrees of freedom according to their physical constraints. The unique coordination patterns of different para swimmers offer an opportunity to explore adaptive strategies and biomechanical adjustments that enable optimal performance for para swimmers. Therefore, the assumption that there is one general optimal pattern of coordination that all swimmers should follow is rejected in this study for para swimmers. Instead, para swimmers and coaches should reconsider their unique coordination patterns as efficient and balanced adaptations to various physical constraints that play a crucial role in shaping competitive performance.

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