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THE GOLD RUSH IN PARA SWIMMING: CHANGES IN THE SPEED CURVE OF A VISUALLY IMPAIRED WORLD AND PARALYMPIC CHAMPION – A CASE STUDY

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ABSTRACT

This case study examined the association between 50 m freestyle and speed curve parameters of a world-class Paralympic swimmer and analyzed the changes in speed curves and their frequency components across performance levels. From 2018 to 2021, a visually impaired female swimmer (26.59 s in 50 m freestyle, S12 class) underwent 22 tests to obtain instantaneous speed synchronized with video recording. She regularly performed 50 m freestyle in competitions and time trials. The fast Fourier transformation method converted the speed signal into frequency domains and determined the relative contribution of the harmonics with two maxima and minima (H2, arms actions) and six maxima and minima (H6, legs actions). The functional paired t-test compared the speed curves at the beginning (PRE) and end (POST) of the analyzed period. The 50 m freestyle time correlated with average speed ($r = -0.50$, $p = 0.02$). The contribution of H6 increased in the first year and remained large, whereas the contribution of H2 was lower throughout the whole period. POST was faster than PRE in five moments that coincide with the downward leg kick moments. These changes allowed her to stay longer at the upper part of the curve and improve performance over time.

Keywords: biomechanics; kinematics; performance; swimming; freestyle

INTRODUCTION

Technique is a pivotal aspect for swimming performance [1] and the analysis of the speed curve is an approach for monitoring the technical progression in swimming [2]. The speed curve fluctuations represent the net result of resistive and propulsive forces and reflect the swimmers' ability to coordinate the propulsive actions of the arms and legs while minimizing sources of resistive forces [3]. Recent studies have demonstrated that changes in the speed curve are associated with competitive performance and provided insights into the technical and physical training of world-class athletes [4,5].

In the para swimming context, the speed curve analysis was used to establish knowledge about classification. For instance, Barbosa et al. [6] utilized the in-water bilateral leg kick speed difference to provide insights into the classification process of a former Paralympic swimmer. The authors concluded that the impact of his impairment on kick performance differs when using quantitative and qualitative assessments. In addition, the analysis of the speed curve can also work as a tool to understand the uniqueness of para swimmers' technique and their performances.

Swimmers with distinct characteristics coordinate the propulsive actions of arms and legs differently, resulting in waveform patterns with specific and individual embedded rhythms. The fast Fourier transformation method can define these rhythms by converting the original speed signal into frequency domains so that the main components of the waveform can be selected [7]. Although the obtained frequency spectra may not directly reflect the physical phenomena, the harmonics of the signal can be associated with the arm and leg actions of the stroke that ultimately causes the speed fluctuation. For instance, the speed signal of a front-crawl swimmer with a six-beat kick pattern per one arm cycle and a stroke rate of 60 cycles per minute is expected to be explained by both the harmonics with two maxima and minima and six maxima and minima. These harmonics would represent the speed fluctuations of arm and leg actions, respectively.

The comparison among speed curves through functional data analysis (FDA) is another approach to explore the speed curve. In FDA, the whole curve is represented by a mathematical function [8]. When the FDA is associated with other statistical methods (e.g., paired t-test), the entire curve can be compared, rather than only isolated speed points [8]. For instance, Barbosa et al [9] analyzed the differences among the speed curves of 23-, 22- and 21-s front-crawl male swimmers and concluded that faster swimmers achieved higher peak speed and stayed longer at the upper part of the curve. In summary, the assessment of the speed signal using both the fast Fourier transformation method and FDA could provide a practical understanding of how Paralympic athletes improve technique and performance over time. It could also shed more light on what is required for a swimmer to improve his/her competitive level.

From 2018 to 2021, we had the unique opportunity to assess the speed curve and video of a visually impaired female swimmer (S12) who improved her sprint performance and became Paralympic and World champion and World record holder in the 50 m freestyle. Therefore, the aims of this case study were: (1) to examine the association between the 50 m freestyle performance and the speed curve parameters of a world-class Paralympic swimmer; and (2) to analyze the changes in the speed curves and their frequency components across her performance levels. We hypothesize that she would reach higher peak speeds and longer periods at the upper part of the speed curve.

MATERIALS AND METHODS

Participant

The female swimmer analyzed herein (age in 2018: 33 years, height: 1.70 m, body mass: 63.5 kg; fat percentage: 11.4%; training experience: 25 years) was enrolled on Para swimming in 2018 in the S12 class. She was born with Morning Glory Syndrome, which causes a defect in the optic nerve, and has fluid accumulation in the retina. Her left eye can only detect shapes whereas the right eye provides no peripheral vision. She won gold medals in the 50 m freestyle (and other races) in Lima 2019 Para Pan-American Games, London 2019 World Para Swimming Championship, and in Tokyo 2020 Paralympic Games. After joining our training program in 2018 with a personal best of 28.02 s in the 50 m freestyle, she swum under the WR in a time trial with electronic timing system in November 2020 (26.59 s) and officially broke the WR in June 2021 (26.72 s). The athlete provided verbal and written informed consent to participate, and the University's Ethics Committee approved all procedures (Process: 74965917.5.0000.5404).

Study design

This is an exploratory retrospective case study. From November 2018 to September 2021 the swimmer underwent technical analysis sessions using instantaneous speed synchronized with video recording. She also had competitions and time trials on a regular basis.

Competitive performance

The 50 m freestyle performances were obtained from time trials and official competitions in long course pools with electronic timing systems. The best time from either the heat or final was retained.

Testing procedures

After a standardized 1000-m warm-up, the swimmer performed one 25 m maximal sprint with no breathing and self-selected stroke rate from an in-water push-off start. A speedometer (CEFISE, Nova Odessa, Brazil, sampling frequency: 250 Hz) attached to her hip at the central point of the lumbar region measured the instantaneous speed during the trial. An underwater cabled camera was attached to either a trolley or to a monopod and recorded the trial at 30 Hz. The trolley was pulled alongside the pool at the same speed as the swimmer, whereas the monopod was positioned at the 15-m mark and was rotated by the operator to record the swimmer's motion. A customized software (Forward®, Meazure Sport Sciences, Brazil) triggered both the camera and speedometer, synchronized their signals, and allowed the speed curve analyses in relation to the stroke movements. The raw data were smoothed with a fourth-order Butterworth low-pass digital filter with a cut-off frequency of 12 Hz determined through residual analysis [10]. After the break-out, one stroke cycle was omitted to attenuate the push-off and underwater kicking effects. The data selection started from next right arm stroke, and the minimum speed value found immediately after hand's entry into the water was used as reference. The next six cycles were used for further analyses. Only assessments that occurred within 20 days of a time trial or competition were considered for analysis.

Kinematics and discrete parameters

Average speed, stroke rate ([6 · 60] / time of the six stroke cycles), stroke length (average speed / stroke rate), and intracyclic speed variation (ISV, i.e., the coefficient of variation of hip speed) were calculated from the six cycles (i.e., 12 arm strokes). Minimum (the minimum speed value found after hand's entry in the water) and peak speeds (the highest speed value between two consecutive minimum speeds) were also obtained in every arm stroke, and the average of both arms was retained for analysis. In nine tests, the athlete performed two or more trials, so we could calculate the coefficient of variation and typical error of measurement (i.e., the standard deviation of the difference score divided by the square root of two), which were 0.9% and 0.01 m/s for average speed, 9.2% of ISV and

1.4% of hip speed for ISV, 3.8% and 0.05 m/s for minimum speed, 1.7% and 0.04 m/s for peak speed, 2.4% and 1.6 cycles/min for stroke rate, 2.1% and 0.04 m for stroke length, respectively.

Frequency analysis

To define the embedded rhythms in the speed curve, the speed signal was converted into frequency domains by fast Fourier transform, which separates the main components of the waveform from the biological noise [7]. The speed signal was detrended and inputted to a Fourier analysis to obtain the Fourier spectrum of the speed signal using "fft" function in MATLAB 2019b (MathWorks, USA), and the obtained frequencies were expressed as relative frequencies (in relation to the stroke cycle time) so that each frequency represents the number of peaks within the stroke cycle. The underwater video analysis confirmed that the swimmer used a six-beat-kick pattern per one complete arm cycle in maximal intensity. Therefore, we particularly focused on a harmonic with two maxima and minima (H2) as well as a harmonic with six maxima and minima (H6) per stroke cycle, assuming that these harmonics represented the speed fluctuations due to arm and leg actions, respectively.

After the Fourier analysis, the relative frequencies were rounded, i.e. 1.51 – 2.49 peaks/cycle signals and 5.51 – 6.49 peaks/cycle signals were considered to be H2 and H6, respectively. This process was slightly different from previous studies [11–13] which utilized Fourier transform to investigate the wave characteristics in front crawl and butterfly. This was based on the rationale that the speed signal was likely much noisier than motion signals due to many small movements affecting the whole-body swimming speed, meaning that only focusing on specific harmonics (such as 2.00 peaks/cycle) without considering a range might underestimate the contribution of each harmonic due to multiple factors such as slight inter-cycle movement variabilities and left and right asymmetries. The power of each Fourier harmonic was calculated by the sum of the squares of frequency amplitudes (e.g. the power of 2 peaks/cycle harmonic was the sum of the amplitudes of 1.51 – 2.49 peaks/cycle signals), and the contribution by each harmonic to the average power of the original signal was obtained and expressed as a percentage value.

Curve comparison

We used the functional paired t-test to compare the speed curves at the beginning (PRE) and end (POST) of her preparation towards Tokyo 2020 and identified which parts of the stroke cycle differed across her performance levels. Functional paired t-test combines the functional data analysis with the analysis of variance so that the whole speed curve is represented by a mathematical function that can be statistically compared with others [8,9]. As she considerably improved her performance in the first training season, the first speed assessments would better represent her initial condition. Therefore, PRE comprised her first three speed curves assessed from October 2018 to February 2019. POST encompassed the three respective speed curves assessed near to her top three best 50 m freestyle performances, which occurred in November 2020, June 2021, and July 2021. The three best performances are not chronologically near to the best performance because they were achieved in different training cycles. This is reasonable since world-class athletes are typically unable to maintain their competitive level near to the world record for too long.

Statistical analysis

Parameters derived from the speed curve were presented as mean ± standard deviation. Shapiro-Wilk test verified data normality, whereas the outlier labelling rule confirmed that there were no outliers [14]. Pearson correlation coefficients assessed the relationships between variables, and significant findings were interpreted as: >0.30: small, 0.31-0.49: moderate, 0.50-0.69: large, 0.70-0.89: very large, and 0.90-1.00: nearly perfect [15]. The significance level was set at $p \leq 0.05$.

A functional paired t-test determined differences between the speed curves of PRE and POST. First, the speed curves were time normalized. Time values were assigned from 0 to 100, which corresponded to the start and end of the speed values of the stroke cycle, respectively. Then, to perform the functional paired t-test analysis, the data was converted into a functional form, i.e., the raw data for observation "i" was used to define the "xi" function, which could be evaluated at all t values over some intervals. Four B-splines with a least-square fitting technique were applied to obtain a smooth and accurate representation of the data, as previously adopted [16]. B-spline functions are more appropriate for noncyclical data values observed at distinct points on a finite interval [16,17]. As the time series of different attempts may vary in phase or amplitude, the average curve may not accurately represent its real behavior. Therefore, the curves were aligned to reduce phase variability while preserving the curves' shape and amplitude. As a standardized procedure, a reference point is defined (which can be a crossover of minimums, maximums, or zero [16]) and used to align all curves, so that the average curve could faithfully represent the trials performed [18]. Herein, the minimum speed was used as the reference point. Then, an average curve of the stroke cycle was generated for PRE and POST by taking the mean of the speed curve at each percentile time point using 18 cycles (number of assessments x six cycles per trial, that is 12 arm strokes). Finally, a functional paired t-test was used in functional contexts according to the equation:

$$\text{Speed } c(t) = \mu(t) + \alpha c(t) + \varepsilon c(t)$$

'μ' indicates the average speed profile in all conditions, 'αc' refers to the specific speed profile of a 'c' condition with two levels (PRE and POST). The residual functional εc is the variation not explained by the model. The analysis resulted in curves of the estimated average effects with 95% confidence intervals throughout the stroke cycle. The comparison indicated significant differences in specific phases of the average speed curves if the confidence interval values did not include the zero line [18]. Functional paired t-test was implemented in Matlab 2017a (MathWorks, USA), as described elsewhere [19].

As the present study only contained one swimmer, the data samples were all dependent, which violated the assumption of the statistical tests. Nevertheless, the aim of the statistical analyses in the present study was not to present the result as a general trend that is applicable to other individuals or groups but to show the change in the swimmer's performance mathematically. Therefore, the violation of the assumption of data independence was not relevant to the present study.

RESULTS

Descriptive data from the kinematics, discrete parameters and 50 m freestyle performances are in Table 1. The swimmer raced the 50 m freestyle 29 times during the study period (Figure 1), obtained six personal best times, improving -2.0%; -0.6%, -0.5%, -0.5%, -0.7% and -0.9% from her previous best time and dropped 5.1% of her initial best time, from 28.02 s to 26.59 s. A total of 22 speed tests were performed close to a time trial or competitions (time difference between competition and testing session: 6.6 ± 6.0 days – Table 1). The 50 m freestyle performance correlated with the average speed assessed with the speedometer ($r = -0.50$, $p = 0.02$, large), but not with peak speed ($r = 0.13$, $p = 0.56$), minimum speed ($r = -0.24$, $p = 0.29$), ISV ($r = 0.12$, $p = 0.60$), stroke rate ($r = 0.12$, $p = 0.59$) or stroke length ($r = -0.40$, $p = 0.06$).

Table 1. Descriptive data from the kinematics, discrete parameters, and 50 m freestyle performances.

Year	Month	Competition	50 m (s)	Diff (days)	AS (m/s)	Peak (m/s)	Min (m/s)	ISV (%)	SR (c/min)	SL (m)
2018	Oct	National	28.02	18	1.59	2.03	1.07	15.8	60.0	1.59
2019	Feb	Time Trial	27.45 *	19	1.58	1.83	1.22	10.7	60.1	1.58
		Regional	27.60	2	1.59	1.88	1.23	11.2	60.5	1.58
	Mar	Regional	27.81	-	-	-	-	-	-	-
		Time Trial	27.81	-	-	-	-	-	-	-
		Regional	28.00	-	-	-	-	-	-	-
		Time Trial	27.28 *	5	1.61	1.90	1.26	10.9	62.7	1.54
	Apr	Regional	27.13 *	12	1.64	1.92	1.35	10.0	61.3	1.60
		National	27.00 *	-	-	-	-	-	-	-
	May	Regional	27.69	3	1.58	1.94	1.16	13.0	61.0	1.56
	Jun	Regional	27.87	2	1.61	1.95	1.20	12.5	63.4	1.53
	Jul	National	27.21	2	1.61	1.85	1.32	11.2	59.7	1.62
	Aug	Time Trial	27.10	6	1.65	1.96	1.28	11.4	63.0	1.57
		Para Pan-American	27.44	-	-	-	-	-	-	-
	Sep	World Championship	27.22	-	-	-	-	-	-	-
	Oct	National	27.56	8	1.59	1.90	1.24	11.9	58.8	1.63
	Nov	Regional	27.63	5	1.61	1.99	1.21	13.9	57.5	1.68
	Dec	Regional	27.40	2	1.64	2.05	1.19	15.0	59.5	1.66
2020	Feb	Regional	27.10	2	1.62	1.91	1.22	11.9	60.0	1.62
		Time Trial	27.03	2	1.63	1.91	1.23	11.2	61.3	1.60
		Time Trial	26.82 *	-	-	-	-	-	-	-
	Mar	Time Trial	27.07	2	1.63	1.91	1.20	11.8	60.1	1.62
	Nov	Time Trial	26.59 *	1	1.63	1.95	1.21	13.0	60.4	1.62
2021	Feb	Time Trial	26.83	4	1.60	1.94	1.11	14.5	59.2	1.62
	Mar	Time Trial	26.98	19	1.61	1.92	1.17	13.3	59.1	1.63
	Apr	Time Trial	27.09	4	1.60	1.95	1.25	12.8	58.6	1.64
	Jun	National	26.72 **	11	1.66	1.87	1.35	9.3	61.8	1.62
	Jul	Time Trial	26.78	4	1.62	1.98	1.26	13.1	60.2	1.61
	Aug	Paralympic Games	26.82	13	1.59	1.98	1.07	16.8	56.6	1.69

* Indicate personal best time; ** Indicate World Record. Diff: time difference between competition and testing session. AS: average speed; Peak: peak speed; Min: minimum speed; ISV: intracyclic speed variation; SR: stroke rate; SL: stroke length

The contribution of H2 and H6 harmonics to the speed signal are shown in Figure 1. Generally, the swimmer had a greater contribution of H6 to the speed signal compared with H2 (mean contributions throughout the period were 43.7% and 15.6%, respectively). meaning that the speed fluctuation was probably caused more by the kick motion than the arm stroke motion. The contribution of H6 increased in August 2019 (the mean H6 contributions were 29.3% and 51.9% before and after August 2019, respectively), and remained high until the end of the monitored period. On the other hand, in the same period, the contribution of H2 was lower and varied from 8.3 to 25.1% (Figure 1). The average speed during the sprint testing before August 2019 was 1.60 m/s, and the average speed after August 2019 was 1.62 m/s.

Figure 1. The contribution by H2 and H6 harmonics to the average power of the original speed signal throughout the study period.

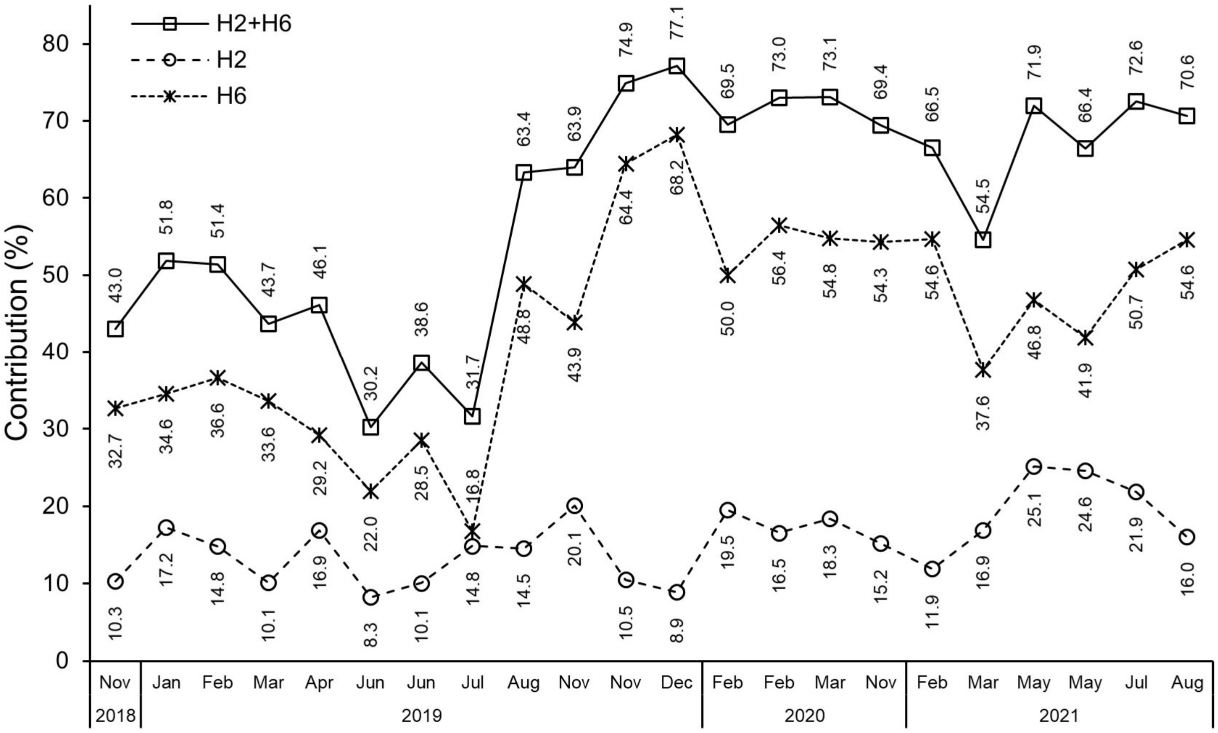


Figure 2. The three individual curves used in PRE (Panel A) and POST (Panel B).

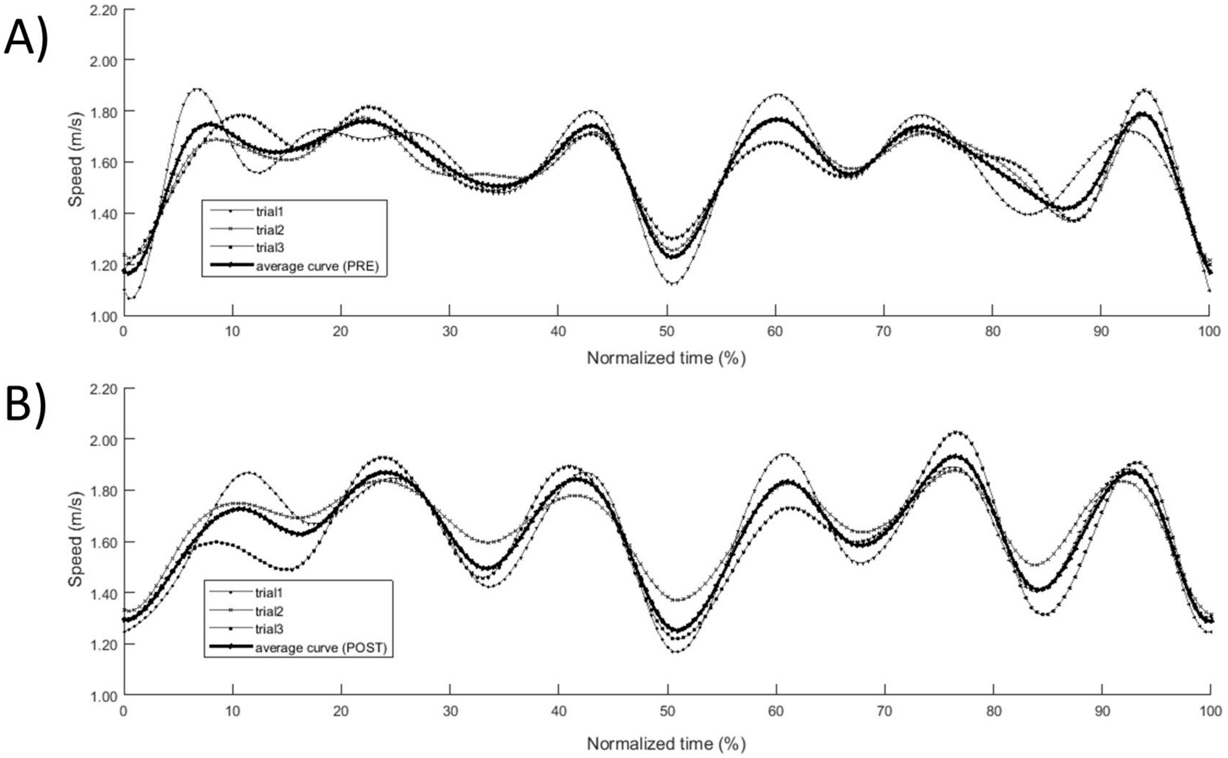
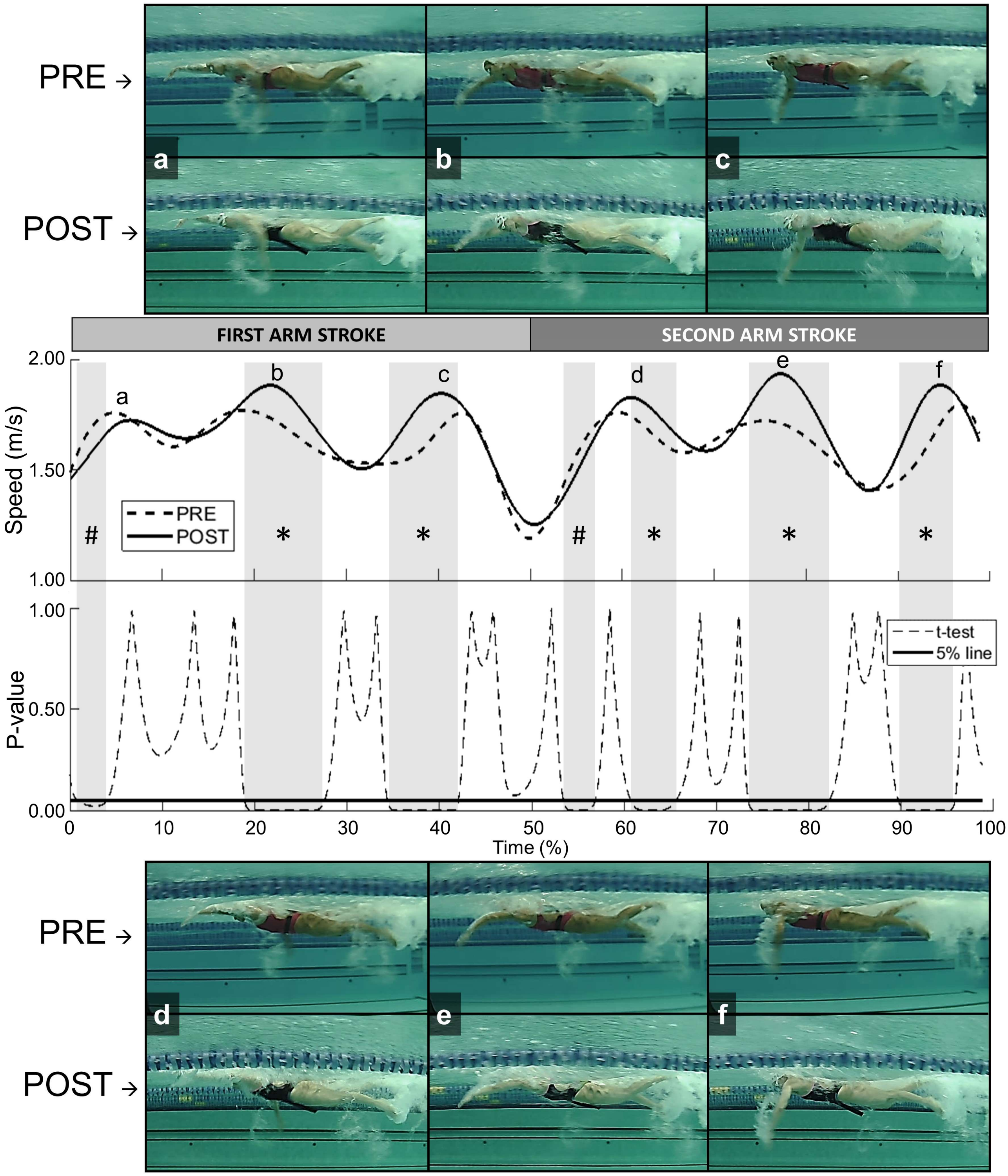


Figure 3. Comparison between the speed curves of one cycle (i.e., arm two strokes) in PRE and POST. Letters from ‘a’ to ‘f’ shown in the graph refer to the stroke positions depicted in the photo sequence. Shaded areas = moments with significant difference between PRE and POST; * POST faster than PRE; # PRE faster than POST.



The three individual curves in PRE and POST are shown in Figure 2. The results of the functional paired t-test (Figure 3) indicate that the curve in POST was faster than PRE in five moments: 19-27%, 35-42%, 61-66%,73-82% and 90-96% of the stroke cycle. Video analysis revealed that these moments coincide with the leg actions. PRE was faster than POST from 1 to 4% and 53 to 57% of the stroke cycle.

DISCUSSION AND IMPLICATIONS

This study examined the relationships between 50 m freestyle performance and speed curve parameters of a world-class Paralympic swimmer. It also analyzed the changes in the speed curve and its frequency components across her performance levels. Our main findings were: 1) 50 m freestyle performance was largely associated with average speed assessed with the speedometer; 2) the contribution of H6 increased at the first year and remained large, whereas the contribution of H2 was lower throughout the whole study period, and 3) the changes in the speed curve occurred in six moments within the stroke that coincide with the downward leg kick moments and allowed her to stay longer at the upper part of the curve.

The comparison between the first and the best assessments (i.e., October 2018 and June 2021, respectively) reveals an improvement of 4.8% in the average speed. Swimming speed is the product of stroke rate and stroke length, but there were no correlations with any of these parameters. Therefore, the speed improvements of the current swimmer occurred due to the combination of both parameters, but the magnitude of changes in each variable varied along the period.

The result of correlation analysis indicates that the 50 m freestyle time decreases as the average speed increases. This result follows previous investigations comprising elite and world-class athletes [5,9]. As average speed is the most relevant performance metric in competitive swimming, its association with competitive performance was expected. On the other hand, the lack of relationship between competitive performance and peak speed is novel. Barbosa et al [9] compared the speed curves of 23-, 22- and 21-s front-crawl male swimmers and suggested that the peak speed differentiates world-class male swimmers. Also, Barbosa et al. [5] reported that the peak speed was associated with the long-term performance changes of an Olympic semifinalist in the 50 m freestyle. Notably, the participants of both studies were males who achieved an average speed of 1.90 m/s or higher [5,9], whereas the current female swimmer reached 1.66 m/s as her best result. Therefore, the difference between the current and previous studies may highlight potential gender or strategic differences. For example, Barbosa et al [9] reported that the world-top male swimmers (21 s in 50 m freestyle) showed intra-cycle speed peaks in the push phase, while this trend was not evident in less-skilled male swimmers (23 s in 50 m front crawl). Even though Barbosa et al [9] did not analyze the speed curve harmonics, their results might imply that H2 but not H6 is the primary component of the speed curve in world-class male swimmers because there are two push phases (i.e. two speed peaks) in one stroke cycle. In other words, the source of the peak speed is different between the current and previous studies, which might cause the difference in the correlation analysis. However, it is unclear if the distinct speed curve patterns were due to the gender, swimming speed, or differences between Olympic and Paralympic swimmers. Further studies comprising Fourier analysis and the speed curve are encouraged and may be helpful to answer this question.

Functional paired t-test revealed that POST was faster than PRE in six moments, in which she reached higher speed values and stayed longer at an upper part of the curve. Considering that this swimmer has a six-beat-kick pattern per one complete arm cycle, her speed signal elicits six maxima and minima (legs) with two maxima and two minima harmonics (arms). The increase of the H6 harmonic over time may indicate a greater contribution of legs to the speed signal and is possibly linked to the differences detected by functional paired t-test.

The leg kick propulsion relates to the ability to generate mechanical power [20], lower limbs dimensions and characteristics [21,22], and technique and coordination [23]. In the early stage of the observational period (i.e., end of 2018 and beginning of 2019), technique and coordination were detected as aspects with potential for improvement for the current swimmer. With qualitative video analysis, we identified that the swimmer rolled her hip segment following the shoulder rotation around the longitudinal axis (Figure 2b). Differently, it has been demonstrated that swimmers tend to roll their shoulders more than their hips in order to increase their speed [24–26]. This movement pattern may reduce the amount of arms and legs fluid forces wasted in non-propulsive directions [25] and diminish both the downward motion of the hip and the active drag [26].

Specific drills were then included in the program so that the athlete could experience and incorporate a different movement pattern. For instance, we used the polo drill, in which the subject swims while maintaining the head above the water surface throughout the whole stroke cycle. Compared to free swimming, the polo drill reduces the relative duration of the entry and catch phase, stroke length and stroke duration, and increases the trunk inclination, hip vertical displacement and the relative duration of the recovery phase [27]. Because the lower limbs play a critical role in maintaining a more aligned body position [28], the lower hip position in the polo drill likely requires an extra effort of the leg kick. The swimmer is then induced to maximize the leg kick force in the swimming direction in order to keep the highest possible horizontal speed.

Our anecdotal experience indicates that the systematic use of this and other drills produced a better connection between the leg kick and the trunk and arm movements. Consequently, the relative contribution of the H6 harmonic for the speed signal increased so that the swimmer could reach higher peaks and stay longer at the upper part of the speed curve in five main moments of the stroke cycle. This change likely led her to improve the average speed, which converted into lower times in the 50 m freestyle.

Interestingly, some average speeds were not high despite the same relative contribution of H2 and H6 harmonics. In these cases, other factors may have influenced her performance. For instance, the intensification of the training in specific periods may generate residual fatigue and reduce performance [29]. Another possibility is that H2 and H6 might not be sufficient to fully explain the changes in the speed on some occasions. For instance, it might be possible that the swimmer changed her technique over time and the acceleration/deceleration patterns due to the arm motion might not have been clearly explained by H2 (i.e., considering higher frequencies such as H3 and H4 might be more suitable depending on the technique). However, without knowing the propulsive force pattern generated by hands, it is not possible to further discuss this possibility. Therefore, it would be of interest to investigate the speed curve and its frequency components together with hand propulsive force (e.g., with pressure sensors) in the future. Finally, as swimmers present different arm-to-leg coordination patterns, it can be suggested that the speed curve works as a personal signature of the swimmer. Therefore, the Fourier analysis might be more revealing for within-subject analyses. In between-subject comparisons, the individual rhythms are more likely to be diluted.

Some limitations may be raised. First, our results apply for the swimmer analyzed and different aspects may be determinant to other swimmers with distinct impairments. Second, we acknowledge that H2 and H6 may not totally and independently represent arms and legs' contribution to the speed fluctuations. Third, although a great part of the signal can be explained by H2 and H6, there is still an important relative contribution (25-30%) of the other frequencies. Finally, the technical diagnoses occurred through qualitative analysis of videos. Certainly, the use of more sophisticated methods could have brough more information about her limbs' actions as well as their interaction. Nevertheless, these methods can be time consuming and difficult to implement in elite level training routines.

CONCLUSION

For this athlete, the average speed assessed through the speedometer was largely related to the 50 m freestyle performance. The contribution of the legs increased over time and influenced her speed curve. These changes allowed her to stay longer at the upper part of the curve and improve performance over time.

REFERENCES

1. Toussaint H, Truijens M. Biomechanical aspects of peak performance in human swimming. *Anim Biol*. 2005;55(1):17-40. doi:10.1163/1570756053276907
2. Barbosa TM, Barbosa AC, Simbaña Escobar D, et al. The role of the biomechanics analyst in swimming training and competition analysis. *Sport Biomech*. 2021;00(00):1-18. doi:10.1080/14763141.2021.1960417
3. Alberty M, Sidney M, Huot-Marchand F, Hespel JM, Pelayo P. Intracyclic velocity variations and arm coordination during exhaustive exercise in front crawl stroke. *Int J Sports Med*. 2005;26(6):471-475. doi:10.1055/s-2004-821110
4. Barbosa AC, Barroso R, Olstad BH, Andrade AG. Long-term changes in the speed curve of a world-class butterfly swimmer. *J Sports Med Phys Fitness*. 2021;61(1):152-158. doi:10.23736/S0022-4707.20.11557-3
5. Barbosa AC, Valadão PF, Wilke CF, et al. The road to 21 seconds: A case report of a 2016 Olympic swimming sprinter. *Int J Sport Sci Coach*. 2019;14(3):393-405. doi:10.1177/1747954119828885
6. Barbosa AC, Araújo LT, Kanayama TOC, et al. The classification in Para swimming: Analysis of a Paralympic champion's withdraw case. *Int J Sport Sci Coach*. 2021;16(1):166-172. doi:10.1177/1747954120953523
7. Sanders RH. Kinematics, coordination, variability, and biological noise in the prone flutter kick at different levels of a "learn-to-swim" programme. *J Sports Sci*. 2007;25(2):213-227. doi:10.1080/02640410600631025
8. Andrade AGP, Polese JC, Paolucci LA, Menzel HJK, Teixeira-Salmela LF. Functional data analyses for the assessment of joint power profiles during gait of stroke subjects. *J Appl Biomech*. 2014;30(2):348-352. doi:10.1123/jab.2013-0147
9. Barbosa AC, Barroso R, Gonjo T, et al. 50 m freestyle in 21, 22 and 23 s: What

differentiates the speed curve of world-class and elite male swimmers? *Int J Perform Anal Sport*. 2021;00(00):1-11. doi:10.1080/24748668.2021.1971509

10. Winter DA. *Biomechanics and Motor Control of Human Movement*. Wiley Interscience; 1990.
11. Sanders RH, Cappaert JM, Devlin RK. Wave characteristics of butterfly swimming. *J Biomech*. 1995;28(1):9-16. doi:10.1016/0021-9290(95)80002-6
12. Gonjo T, Kishimoto T, Sanders R, Saito M, Takagi H. Front crawl body roll characteristics in a Paralympic medallist and national level swimmers with unilateral arm amputation. *Sport Biomech*. 2019;00(00):1-17. doi:10.1080/14763141.2019.1654536
13. Sanders RH, Psycharakis SG. Rolling rhythms in front crawl swimming with six-beat kick. *J Biomech*. 2009;42(3):273-279. doi:10.1016/j.jbiomech.2008.10.037
14. Hoaglin DC, Iglewicz B, Tukey JW. Performance of some resistant rules for outlier labeling. *J Am Stat Assoc*. 1986;81(396):991-999. doi:10.1080/01621459.1986.10478363
15. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41(1):3-12. doi:10.1249/MSS.0b013e31818cb278
16. Ramsay J, Silverman B. *Functional Data Analysis*. 2nd ed. Springer; 2005.
17. Melo C, Carpes F, Vieira T, et al. Correlation between running asymmetry, mechanical efficiency, and performance during a 10 km run. *J Biomech*. 2020;109:109913. doi:10.1016/j.jbiomech.2020.109913
18. Røislien J, Skare Ø, Gustavsen M, Broch NL, Rennie L, Opheim A. Simultaneous estimation of effects of gender, age and walking speed on kinematic gait data. *Gait Posture*. 2009;30(4):441-445. doi:10.1016/j.gaitpost.2009.07.002
19. Ramsay JO, Hooker G, Graves S. *Functional Data Analysis with R and MATLAB*. Springer; 2009.
20. Toussaint HM. Differences in propelling efficiency between competitive and triathlon swimmers. *Med Sci Sport Exerc*. 1990;22(3):409-415.
21. Kjendlie PL, Stallman R. Morphology and swimming performance. *World B Swim From Sci to Perform*. 2011;(January 2011):203-221.
22. Shimojo H, Nara R, Baba Y, Ichikawa H, Ikeda Y, Shimoyama Y. Does ankle joint flexibility affect underwater kicking efficiency and three-dimensional kinematics? *J Sports Sci*. 2019;37(20):2339-2346. doi:10.1080/02640414.2019.1633157

23. Silveira RP, de Souza Castro FA, Figueiredo P, Vilas-Boas JP, Zamparo P. The effects of leg kick on swimming speed and arm-stroke efficiency in the front crawl. *Int J Sports Physiol Perform*. 2017;12(6):728-735. doi:10.1123/ijspp.2016-0232
24. Psycharakis SG, Sanders RH. Shoulder and hip roll changes during 200-m front crawl swimming. *Med Sci Sports Exerc*. 2008;40(12):2129-2136. doi:10.1249/MSS.0b013e31818160bc
25. Yanai T. Stroke frequency in front crawl: Its mechanical link to the fluid forces required in non-propulsive directions. *J Biomech*. 2003;36(1):53-62. doi:10.1016/S0021-9290(02)00299-3
26. Cappaert JM, Pease DL, Troup JP. Three-dimensional analysis of the men’s 100-m freestyle during the 1992 Olympic Games. *J Appl Biomech*. 1995;11(1):103-112. doi:10.1123/jab.11.1.103
27. Brackley V, Tor E, Barris S, et al. The effect of polo drill swimming on freestyle kinematics : a pilot study. *ISBS Proc Arch*. 2020;38:528-531.
28. Gourgoulis V, Boli A, Aggeloussis N, et al. The effect of leg kick on sprint front crawl swimming. *J Sports Sci*. 2014;32(3):278-289. doi:10.1080/02640414.2013.823224
29. Aubry A, Hausswirth C, Louis J, Coutts AJ, Le Meur Y. Functional overreaching: The key to peak performance during the taper? *Med Sci Sports Exerc*. 2014;46(9):1769-1777. doi:10.1249/MSS.0000000000000301