BODY WAVE CHARACTERISTICS AND VARIABILITY OF AN INTERNATIONAL AND A REGIONAL LEVEL SWIMMER IN 50 M BUTTERFLY SWIMMING

Tomohiro Gonjo and Bjørn Harald Olstad

Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Noway

The purpose of this study was to compare body wave characteristics between butterfly swimmers with different competitive levels as a case study. An international and a regional level swimmer performed a 50 m butterfly with their maximum effort, and their one stroke cycle velocity, stroke frequency, stroke length, and the vertical coordinate of the shoulder, hip, knee, and ankle joint were quantified for each stroke. The vertical coordinate data were analysed by a Fourier analysis to establish the amplitude, phase angle, contribution to the total signal of harmonic with one maxima/minima (due to one arm stroke motion in a cycle: H1) and two maxima/minima (related to two kicks in a cycle: H2). The velocity of each harmonic travelling caudally between shoulder and hip, hip and knee, and knee and ankle was also obtained. The international swimmer was faster by 23% with 17% longer stroke length and 6% higher stroke frequency than the regional swimmer. The international swimmer was also characterised by lower inter-stroke variability in the amplitude, contribution, and wave velocity of H1 and H2, suggesting that the international swimmer has a more stable rhythm and coordination between the upper and lower body compared with the regional swimmer. The international swimmer had a larger contribution of H1 to the vertical shoulder motion than the regional swimmer, meaning that the kick motion of the international swimmer originates from a more cephalic part of the body compared with the regional swimmer. The international swimmer generated the shoulder H1 rhythm for one stroke cycle at the end of the preceding cycle whereas the regional swimmer produced the shoulder H1 rhythm at the beginning of each cycle, which might be a reason for the higher stroke frequency of the international swimmer compared with the regional swimmer.

KEYWORDS: kinematics, coordination, rhythm, Fourier analyis

INTRODUCTION: In competitive swimming, butterfly stroke is a unique technique that requires swimmers to propel at the water surface not only with upper and lower limb motions, but also with an undulatory motion. Undulatory motion during swimming is characterised by temporally sequenced oscillations passing along a swimming body caudally that generates an undulatory wave (body wave). The body wave transfers momentum to the surrounding water resulting in a propulsive impulse (McHenry, Pell, & Long, 1995). It has been reported that elite swimmers combine body wave harmonics with one maxima/minima (H1) and two maxima/minima (H2) in one stroke cycle because swimmers perform two leg kicks and one arm pull in one stroke cycle (Sanders, Cappaert, & Devlin, 1995). Sanders et al. (1995) also suggested that elite swimmers reuse the potential energy produced by the vertical motion of the upper body for leg kick propulsion by transferring the body wave along the body caudally. This theory implies the possibility that the wave characteristics could be a determinant of butterfly swimming performance. Since Sanders et al. (1995) only investigated one stroke cycle of international level swimmers, it would be of interest to investigate the wave characteristics of complete butterfly stroke cycles during a race condition in swimmers with different skill levels. The purpose of this study was to assess and compare the wave characteristics between butterfly swimmers with different competitive levels as a case study.

METHODS: An international level swimmer (age: 18 years; height: 1.86 m; weight 75.2 kg; 50 m butterfly FINA point: 845) and a regional level swimmer (age: 17 years; height: 1.79 m; weight 77.1 kg; 50 m butterfly FINA point: 429) participated in this study. After self-selected warm-ups and a set of anthropometric measurements (including height, weight, and the length of each body segment), they performed a 50 m butterfly with their maximum effort in a 25 m pool. The entire 50 m race was recorded by the AIM race analysis system (AIMSys Sweden AB, Lund, Sweden). The system consisted of five above the water and five underwater fixed cameras, which provides one panning video of the entire race (from the view perpendicular to the swimmer) and the instantaneous head velocity (synchronised with the panning video) with 50 Hz after post-processing in the manner described by Haner, Svärm, Ask, & Heyden (2015). From the panning video, the timing of the hand entry to the water was quantified as the start and the end of each stroke cycle. The mean one stroke cycle velocity, stroke frequency, and stroke length were quantified using the head velocity data and the hand entry timing for each stroke throughout the 50 m. The shoulder, hip, knee, and ankle joints of the swimmers were manually digitised using the panning video, and the two-dimensional vertical camera coordinates of each joint were obtained. The obtained camera coordinate of each joint was smoothed at 6Hz by a 2nd order recursive Butterworth digital filter. The smoothed coordinate data were divided into each stroke cycle. The camera coordinate data of each cycle was scaled using the length of the shank of each swimmer and the vertical amplitude of the ankle was quantified. The scaled vertical coordinate data were then demeaned and input to a Fourier analysis to obtain the cosine and sine coefficients of Fourier frequencies (harmonic) of H1 and H2 (Sanders et al., 1995). Amplitude and the phase angle of each harmonic were obtained by equation 1 and 2, respectively.

$$C_n = \sqrt{(A_n^2 + B_n^2)} \qquad (1)$$

$$\varphi = tan^{-1}(B_n \,/\, A_n) \qquad (2)$$

Where C_n, A_n, and B_n are the amplitude and cosine and sine coefficients for the *n*th Fourier frequency, and φ is the phase angle. The average power of each frequency was obtained by $2C_n^2$ and used to calculate the contribution of each harmonic to the total signal power. The phase angle of 0 and 360° indicates the beginning and the end of the cycle. The body wave velocity was determined by dividing the length of each segment (upper body, thigh, and shank) by the time taken for the oscillation of a caudal landmark to achieve the same phase angle as a cephalic landmark. The wave velocity was calculated between the shoulder and hip, hip and knee, and knee and ankle. The mean, standard deviation (SD), and coefficient of variation (CV) of each variable among all stroke cycles were calculated to describe the differences between the swimmers. The first and last stroke cycle in each lap was excluded from the analysis to avoid the potential effect of the swimmers adjusting their strokes for the transition from the water to the surface and the wall touch.

RESULTS: The one stroke cycle velocity, stroke frequency, stroke length, and ankle amplitude of the two swimmers are displayed in Table 1. The international swimmer had 23% faster velocity, 17% longer stroke length, and 6% higher stroke frequency than the regional swimmer with lower CV values that was particularly evident in stroke frequency. The vertical amplitude of the ankle was 9% larger in the international than in the regional swimmer. Table 2 and 3 show the amplitude, phase angle, and the contribution of H1 and H2, respectively. CV of the amplitude of H1 tended to be larger in the regional than in the international swimmer by 9-23%. CV of H2 amplitude also had the same tendency, but this was not as evident as H1 (0.3-12%). The phase angle shows that both swimmers had a tendency of transferring H1 and H2 caudally (from shoulder to ankle). However, the regional swimmer produced shoulder H2 at the phase angle of around 40° (the beginning of the cycle) whereas the international swimmer generated it at around 356° phase angle (the end of the cycle). The contribution of H1 and H2 illustrated that the primary harmonic for shoulder vertical motion was H1, whereas that for the hip, knee, and ankle joint was H2. However, the international swimmer had 8% larger H2 contribution to the shoulder vertical motion than the regional swimmer. Both swimmers had larger wave velocity CV values in H1 than in H2 (Table 4). This was particularly the case for the hip-knee and knee-ankle H1 velocity in the regional swimmer, where SD values were almost as large as the mean. Shoulder-hip H1 velocity was five times higher in the international than the regional swimmer. Both swimmers tended to increase H2 velocity from shoulder-hip to hip-knee then slow it down at knee-ankle.

Table 1: One stroke cycle velocity, stroke length, and stroke frequency of the swimmers.

	International Swimmer			Regional Swimmer		
	Mean	SD	CV	Mean	SD	CV
One stroke cycle velocity (m/s)	1.908	0.068	3.574	1.516	0.061	4.005
Stroke frequency (cycles/min)	59.565	0.831	1.395	56.332	2.402	4.264
Stroke length (m/cycle)	1.922	0.077	3.992	1.617	0.074	4.552
Ankle amplitude (m)	0.431	0.033	7.631	0.394	0.036	9.206

SD, standard deviation; CV, coefficient of variation

Table 2: Amplitude, phase angle, and contribution (to the vertical joint motion) of one maxima/minima harmonic (H1) in each joint of the swimmers.

		International Swimmer				Regional Swimmer			
		Shoulder	Hip	Knee	Ankle	Shoulder	Hip	Knee	Ankle
Amplitude (m)	Mean	0.053	0.014	0.035	0.036	0.059	0.011	0.023	0.031
	SD	0.003	0.005	0.004	0.005	0.012	0.005	0.009	0.011
	CV	6.373	36.437	11.086	14.488	20.671	49.619	36.820	34.459
Phase angle (°)	Mean	90.649	187.05	288.21	337.41	105.48	244.77	315.22	348.00
	SD	5.056	25.014	6.058	9.845	7.928	46.031	18.631	19.528
	CV	5.578	13.373	2.102	2.918	7.516	18.806	5.910	5.611
Contribution (%)	Mean	83.670	20.112	32.262	14.540	93.193	19.406	20.297	13.954
	SD	3.335	9.129	5.098	3.152	3.290	15.313	11.427	8.109
	CV	3.986	45.388	15.801	21.680	3.531	78.908	56.300	58.117

SD, standard deviation; CV, coefficient of variation

Table 3: Amplitude, phase angle, and contribution (to the vertical joint motion) of two maxima/minima harmonic (H2) in each joint of the swimmers.

		International Swimmer				Regional Swimmer			
		Shoulder	Hip	Knee	Ankle	Shoulder	Hip	Knee	Ankle
Amplitude (m)	Mean	0.022	0.027	0.047	0.084	0.014	0.022	0.046	0.079
	SD	0.002	0.003	0.003	0.006	0.003	0.004	0.005	0.006
	CV	9.441	11.454	6.822	7.573	21.116	16.456	10.348	7.871
Phase angle (°)	Mean	356.09	183.05	252.39	349.92	39.535	210.95	289.51	27.993
	SD	13.411	14.422	15.597	12.695	15.882	13.876	11.387	9.677
	CV	3.766	7.879	6.180	3.628	40.171	6.578	3.933	34.568
Contribution (%)	Mean	14.926	74.997	57.956	77.076	6.461	77.811	76.595	83.545
	SD	3.168	9.175	5.295	2.330	3.274	16.565	11.779	8.867
	CV	21.225	12.234	9.136	3.023	50.665	21.289	15.379	10.614

SD, standard deviation; CV, coefficient of variation

Table 4: Velocity of one and two maxima/minima harmonics (H1 and H2, respectively) travelling through the body caudally between each joint.

		International Swimmer			Regional Swimmer		
		Shoulder-Hip	Hip-Knee	Knee-Ankle	Shoulder-Hip	Hip-Knee	Knee-Ankle
H1	Mean	3.395	1.657	3.024	0.617	3.082	5.530
	SD	0.492	0.282	0.522	0.062	2.175	5.376
	CV	14.505	16.997	17.260	10.106	70.561	97.208
H2	Mean	1.809	2.344	1.482	1.796	1.956	1.641
	SD	0.041	0.132	0.052	0.163	0.161	0.073
	CV	2.293	5.651	3.504	9.052	8.250	4.460

SD, standard deviation; CV, coefficient of variation

DISCUSSION: This study aimed to compare the wave characteristics in butterfly swimming between an international and a regional swimmer. The international swimmer achieved faster swimming velocity than the regional swimmer due to the higher stroke frequency and particularly to the longer stroke length. The longer stroke length might be related to the kicking technique of the swimmers. The international swimmer had 8% larger H2 contribution to the shoulder vertical motion than the regional swimmer, meaning that the kicking motion of the international swimmer was probably originated at a more cranial part of the body than the national swimmer. This implies that the international swimmer might utilise a better kinetic chain strategy that generates a large end-effecter (i.e. ankle) velocity, consequently, a large propulsive force. A larger end-effector velocity in the international swimmer than the regional swimmer was supported by the higher stroke frequency and the larger ankle vertical amplitude of the international swimmer. Obviously, upper-limb motion affects the propulsion and stroke length largely in butterfly stroke. Therefore, it is unclear to what extent the difference in the leg kick between the swimmers affected the stroke length. Further study with a hydrodynamic approach would be required to explore this possibility.
Overall, the international swimmer had smaller variability of the investigated variables, which suggests that the international swimmer had a more stable kinematic strategy than the national swimmer during the race. Large variabilities in the wave velocity and phase angle of the regional swimmer show that this swimmer did not have a constant upper and lower body coordination pattern during the race, and the large H1 and H2 amplitude variabilities illustrate that the swimmer had an unstable up and down motion pattern during the race. Vertical motion during swimming is determined by the balance between the gravity and buoyancy acting on the body as well as the hydrodynamic force produced by the swimmer. Since the gravitational and buoyant forces are related to the anthropometry of the swimmer, the variation of H1 and H2 amplitude was likely due to the vertical components of the hydrodynamic force that does not directly contribute to the forward propulsion. Therefore, the H1 and H2 amplitude variability might reflect that the regional swimmer wasted more energy towards the non-propulsive direction, which is also a potential reason for the difference in the stroke length between the swimmers. Another interesting finding was the difference in the H2 phase angle at the shoulder joint. Even though both swimmers had the same caudal wave transmission pattern, the international swimmer initiated the H2 wave motion at the end of each stroke cycle whereas the national swimmer started the motion at the beginning of the stroke cycle. This difference might show a strategy of the international swimmer to achieve high stroke frequency. Producing H2 wave motion at the end of the stroke cycle can be, in other words, considered as generating the H2 rhythm of a stroke cycle at the end of the preceding cycle. This strategy can potentially shorten the cycle duration and might have linked to the higher stroke frequency of the international swimmer than the national swimmer.

CONCLUSION: The international swimmer had a smaller motion variability than the regional swimmer during 50 m butterfly with a race condition. The international swimmer was also characterised by a large H2 wave contribution at the shoulder, which implies an effective kinetic chain strategy for the leg kick. The international swimmer also achieved a high stroke frequency, i.e., short cycle duration, potentially by producing H2 rhythm at the end of each stroke cycle for the subsequent stroke rather than generating it at the beginning of each cycle.

REFERENCES

Haner, S., Svärm, L., Ask, E., & Heyden, A. (2015). Joint under and over water calibration of a swimmer tracking system. *Proceedings of the International Conference on Pattern Recognition Applications and Methods, 2*, 142-149.

McHenry, M. J., Pell, C. A., & Long, J. H., Jr. (1995). Mechanical control of swimming speed: stiffness and axial wave form in undulating fish models. *J Exp Biol, 198*(Pt 11), 2293-2305. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/9320209

Sanders, R. H., Cappaert, J. M., & Devlin, R. K. (1995). Wave characteristics of butterfly swimming. *J Biomech, 28*(1), 9-16. doi:10.1016/0021-9290(95)80002-6