Acta of Bioengineering and Biomechanics
Vol. 15, No. 1, 2013

Original paper
DOI: 10.5277/abb130114

Symmetry of support scull and vertical position stability in synchronized swimming

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Maintaining the body underwater in the so-called vertical position, where the body is inverted (head down) and balanced, is made possible by performing the support scull movement by the upper limbs. In synchronized swimming, the main criteria for judging this vertical position are maintaining body stability and the maximum height of the lower limbs one is able to extend out of the water. Therefore, it seems important to examine for any correlations between the symmetry of the upper limb's movement (sculling) and the ability to maintain balance of the body. The aim of this study was to use a dynamical asymmetry index (DAI) to assess the symmetry of the upper limb movements performed in synchronized swimming.

The use of the dynamical asymmetry index is considered to be advantageous over the asymmetry coefficient, which is better known in literature on the subject and has been used by numerous authors, as it not only evaluates the magnitude of the asymmetry, but also indicates in which phases of movement asymmetry is the greatest or where it is the least significant.

Key words: *dynamical asymmetry index (DAI), stability, synchronized swimming*

1. Introduction

Synchronized swimming is a discipline of swimming and gymnastics in which swimmers compete by executing a specific routine composed of numerous technical elements (Gray [5]). These technical elements can be divided into those performed with the head above the water surface, and those with the head submerged and the upper limbs elevated out of the water. An analysis of the related literature shows that research on the technique of swimming and maintaining the body with the head above the water has been fairly well examined (Arellano et al. [1]; Homma and Homma [8], [11]; Homma [13]; Kubo et al. [17]). This stems from the fact that this way of positioning the body is similar to that in water polo players and has been a subject of considerable interest. However, maintaining the body inverted under water is made possible by the use of different body movement, which uses the upper limbs to produce a motion called sculling. The technique of performing sculls is critical in keeping the lower body balanced over the submerged head and high above the water (Homma [12]; Homma and Homma [10], [9]).

On the basis of previous research on the kinematic structure of sculling in synchronized swimming, it was found that sculling is a symmetrical and cyclical movement composed of two phases (Homma and Homma [7]). The first phase is to the outside, with an external rotation of the shoulders and an abduction of the forearms. The second phase of movement is towards the inside, with an internal rotation of the shoulders and an adduction of the forearms. Initially, this movement begins in the transverse plane and finishes slanted slightly upward. A significant change in the joint angles occurs during the transition of sculling from the outside to the inside (Francis and Smith [4];

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Received: March 5th, 2012
Accepted for publication: November 18th, 2012

Homma and Homma [10]). An increase in hand speed was also observed, which reached its maximum during the transition from the inside to the outside, but there were no differences in the average hand speed while sculling from the outside to the inside (Homma and Homma [10]). The wrist movement was found to have greater amplitude and speed than that of the hand (the duration of the motor cycle was shorter) when compared to other positions (Hall [6]).

As was mentioned, underwater sculling movements are performed to keep the body inverted vertically with the head under water while stabilizing the body's center of gravity. Due to the nature of synchronized swimming, a swimmer has no point of support to stabilize their body in the water (Rostkowska et al. [22]). Therefore, it can be assumed that any movement asymmetry of the upper limbs will have an effect on a swimmer's overall stability and movement fluidity, which translates into receiving lower scores from judges.

Therefore, the main aim of this study was to present a method for assessing the movement symmetry of the upper limbs during support scull in the vertical position. It was hypothesized that a measurement of the dynamical asymmetry of the upper limbs can make use of the asymmetry coefficient, which had been previously discussed in literature (Robinson et al. [21]; Chen et al. [3]), but modified in this study for measuring the angular movements of the upper limbs' joints. The use of the dynamical asymmetry index is considered to be advantageous over the asymmetry coefficient, which is better known in literature (Szpala et al. [25]), as the DAI not only evaluates the magnitude of the asymmetry, but also indicates in which phases of movement the asymmetry is greatest or points to where it is insignificant.

2. Materials and methods

The study group consisted of synchronized swimmers who finished at least their third year of sports studies in this discipline (n = 15). The average age of the subjects was 15.9 ± 3.5 years, mean body weight and height were 51.9 ± 6.2 kg and 160.6 ± 6.2 cm, respectively. The legal guardians of those subjects who were minors provided written consent to participate in the study. The study also received the approval by the University's Ethics Committee. The subjects were allowed to familiarize themselves with the environment and test conditions during a warm-up. All of the swimmers wore swimsuits, caps, goggles and nose clips.

The study was conducted at the Indoor Swimming Pool at the University School of Physical Education in Wrocław, Poland. The swimmers were filmed at 50 frames per second on videotape as they performed the support scull in the upside down vertical position. Two cameras were placed in watertight enclosures and mounted on tripods at right angles to each other. After the cameras were positioned, a three-dimensional frame

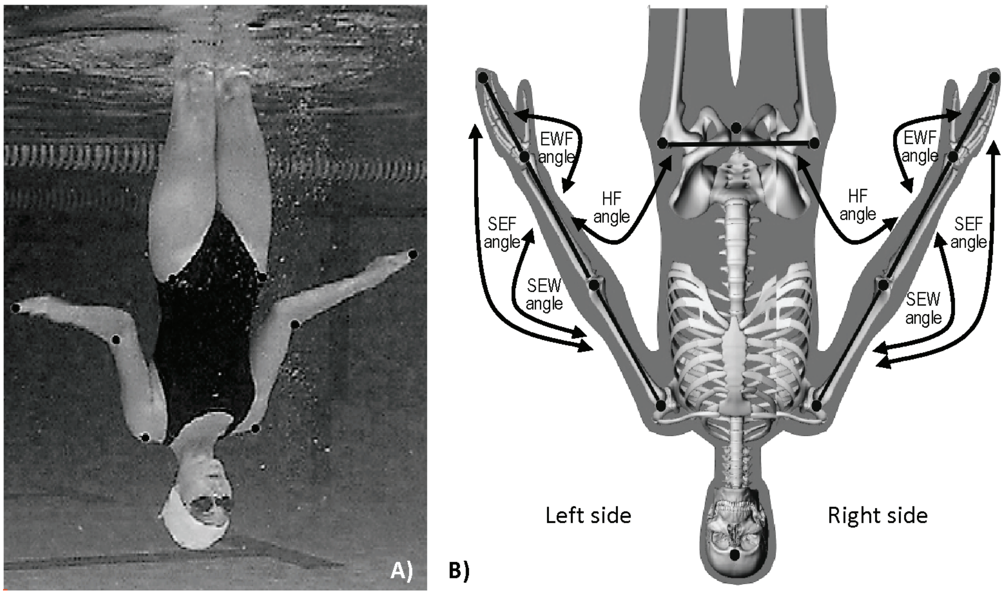

Fig. 1. Photo of a contestant in a head-down, vertical position with 12 markers attached to her main body landmarks, which matches the pubic symphysis, two middle fingers, head and the shoulder, ankle, wrist and hip joints (A), and a corresponding diagram containing the angles analysed: wrist flexion-extension angle (EWF), elbow flexion-extension angle (SEW), sculling angle (SEF), arm rotation angle (HF) for the left and right side (B)

of reference was used to monitor movement in the pool, which consisted of a cube (1 m/1 m/1 m) with six selected reference coordinates. Each measurement was synchronized with a flash of light, placed in the field of view of both cameras. Each of the test subjects had twelve markers placed on their body to measure movement (Fig. 1A).

Before the test measurements, every study subject took part in a warm-up. The test consisted of three trials; each trial entailed performing eight cycles of support scull by the upper limbs in the vertical position with both lower limbs extending out of the water. In total, 360 cycles of performing support scull were collected for statistical analysis, with the data analyzed using SIMI Motion® software (SIMI Reality Motion GMBH, Germany). The upper limb movement of support scull that was primarily measured in this study was the abduction and adduction of the forearms when flexed at the elbows at the necessary angles, with the following components taken into consideration:

- the swimmer's body movement (the displacement of the top of the head and the pubic symphysis during sculling) in three orthogonal directions;
- the normalized range of motion when flexing and extending the elbow joint (the SEW angle), angle calculated by three markers placed on the shoulder, elbow and wrist joints for both the right and left arm;
- the normalized range of motion when flexing and extending the elbow joint, known hereafter as the *sculling angle*, calculated by three markers placed on the shoulder, elbow joints and finger (the SEF angle) for both the right and left arm;
- the normalized range of motion when flexing and extending the wrist joints, calculated by three markers placed on the elbow, wrist joints and finger (the EWF angle) for both the right and left arm;
- the normalized angle between the hips and forearms (the HF angle), known hereafter as the *arm rotation angle*, calculated as an angle between two vectors with one marker placed on right and left anterior superior iliac spine (Vector 1) and on the elbow and wrist joints (Vector 2) for both the right and left arm.

The criteria for dividing support scull into cycles were due to the change in the elbow joint angle, which was demonstrated by the markers' movement located on the axis of the shoulder and elbow joints and at the end of the middle finger (Fig. 1A). It was assumed that a support scull movement cycle corresponds to a change in the sculling angle from the maximum flexion of the elbow joint to the angle of the elbow extended out to its maximum (Phase 1) and then from the maximum extension to the maximum flexion of the elbow joint (Phase 2), which also marks the beginning of the next cycle. The obtained temporal values of the cycles and phases of the sculling angle were regarded as the basis for designating the rest of the parameters analyzed in this study.

2.1. Numerical calculation of the dynamical asymmetry index

Given the differentiation of the values of kinematic motion between the right and left upper limbs during sculling, the symmetrical characteristics were calculated by using a variant of the asymmetry coefficient (Robinson et al. [21]; Chen et al. [3]), modified for the angular movements of the upper limb joints. This dynamical asymmetry index (DAI) expresses the percentage difference between the angles of the swimmer's left $A_L(t)$ and right $A_R(t)$ upper limbs during the cyclical variation of movement, by the formula:

$$DAI(t) = \frac{A_L(t) - A_R(t)}{\frac{1}{2} \cdot [A_L(t) + A_R(t)]} \cdot 100\% . \tag{1}$$

When the value of the dynamical asymmetry index gets close to 0% it stands for perfect symmetry, when it reaches infinitely larger values it indicates maximum asymmetry in the movement. The DAI is a function of time and requires cyclical variation of the right and left angles during an equal duration of time. A positive value of DAI indicates that the magnitude of a left angle was greater than on the right, while a negative DAI indicates that the right side's value was greater. Normalization of the right and left angles relative to the duration of the cycle was performed numerically by the decomposition of a time series (trend detection) using the Lagrange interpolation polynomial as a function of the user. All angles were presented as the percentage of a sculling cycle. The DAI's rate of change (DAI Rate) was calculated numerically using the following formula

$$DAI\ Rate(t) = \frac{DAI(t_{i+1}) - DAI(t_i)}{t_{i+1} - t_i}, \tag{2}$$

where $DAI(t_{i+1})$ is the value of the dynamical asymmetry index for time t_{i+1}, $DAI(t_i)$ is the value of the dynamical asymmetry index for time t_i, where i is a number in the normalized interval, with $t \in \langle 0,100 \rangle$. The rate of change of the DAI Rate accurately describes the changes of the DAI. For example, a DAI Rate equal to zero indicates stability in the DAI, a negative DAI Rate points to the rate at which asymmetry (measured by DAI) decreases, while a positive

DAI Rate indicates an increase in the rate of asymmetry of the limbs movement.

2.2. Statistical calculations

The data collected were examined for statistically significant differences by a normality test (Kolmogorov–Smirnov test) and a test of the equality of group variance (Brown–Forysthe test), as well as examining the significance of the differences of the selected features by the non-parametric Wilcoxon signed-rank test. Linear correlation analysis was performed to study the relationship between the range of motion of each joint and the amount of asymmetry as well as between the range of motion and the magnitude of the rate of asymmetrical change.

All analysis and calculations were performed at the Laboratory of Biomechanical Analysis at the University School of Physical Education in Wrocław, Poland, which is ISO-9001 certified.

3. Results

Table 1 summarizes the results of the mean change in three orthogonal directions of the markers located on the head and pubic symphysis. The largest displacement of the head was in the vertical direction (on average, 4.6 cm), followed by the lateral direction (3.4 cm). The pubic symphysis marker moved the most in the anteroposterior direction (on average, 4.4 cm) and the least in the lateral direction (3.1 cm).

Table 1. Average displacement and +/– standard deviation for the points marked on the head and pubic symphysis in the three main directions for $N = 15$ contestants

Direction of movement	Head marker displacement [m]	Public symphysis marker displacement [m]
Vertical	0.046 ± 0.02	0.038 ± 0.02
Anterior-posterior	0.045 ± 0.03	0.044 ± 0.03
Lateral	0.034 ± 0.01	0.031 ± 0.01

Not significant ($p < 0.01$) between movement of the head and pubic symphysis.

Figure 2 shows the variation of the sculling angle (SEF), the angle at the elbow (SEW), the wrist (EWF) and the lateral/medial rotation of the arm (HF) during the support scull cycles for both left and right upper limbs. Table 2 contains the mean values of the results distribution for each swimmer: the minimum value (Min angle), the maximum value (Max angle) and range of variation (Range) for the

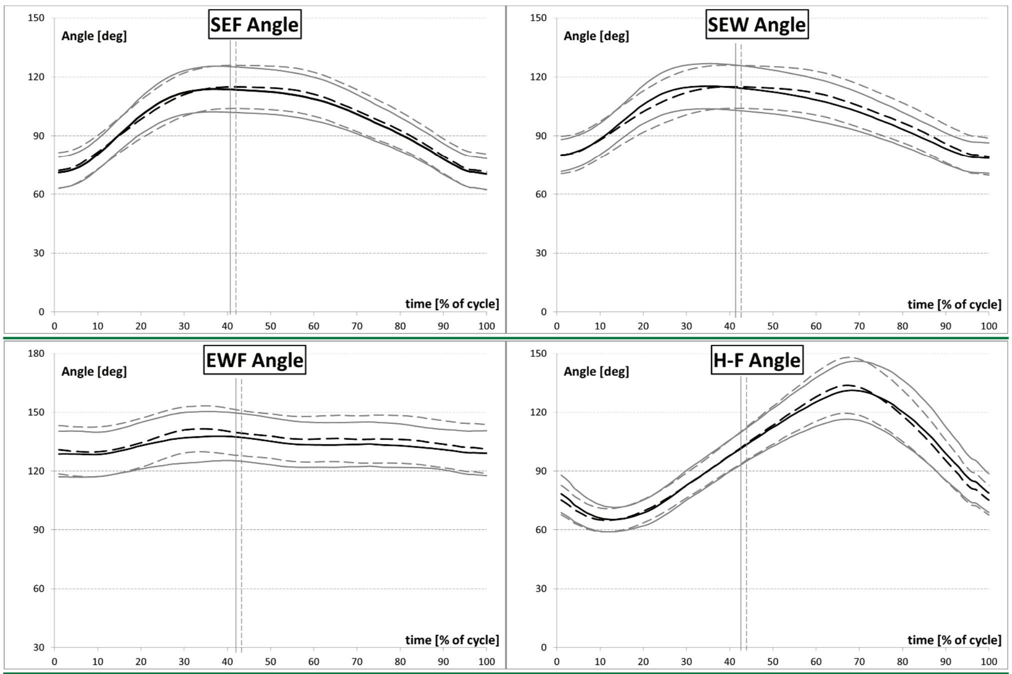

Fig. 2. The range of variation in sculling angle (SEF), elbow flexion-extension angle (SEW), wrist flexion-extension angle (EWF), and arm rotation angle (HF) for the left (thick line) and the right limb (thick dashed line) in sculling cycles and for $N = 15$ contestants. Thin solid and dashed lines indicate +/– standard deviation from the mean. The two vertical lines divide the left (solid) and right (dashed) sculling cycles into two phases: extension and flexion of the elbow joint

left and right limbs. On the right side of the table the average minimum, maximum and range of variation values are presented.

Table 2. Distribution of the minimum (Min angle), maximum (Max angle) and range of change (Max–Min) for sculling angle (SEF), elbow flexion-extension angle (SEW) wrist flexion-extension angle (EWF) and arm rotation angle (HF) for the left and right side and for $N = 15$ contestants

Angle		Left side		Right side	
		mean	±SD	mean	±SD
SEF angle	Min angle [°]	70.4	8.0	71.5	9.2
	Max angle [°]	113.9	11.2	114.9	11.0
	Range [°]	43.4	6.5	43.4	5.9
SEW angle	Min angle [°]	78.6	7.9	79.4	9.6
	Max angle [°]	115.3	10.6	115.0	11.1
	Range [°]	36.7	5.0	35.6	5.3
EWF angle	Min angle [°]	128.4	10.9	129.7	12.3
	Max angle [°]	137.8	12.0	141.6	11.9
	Range [°]	9.4	2.7	11.9	2.2
HF angle	Min angle [°]	65.2	6.5	64.9	6.4
	Max angle [°]	131.2	13.3	133.7	12.5
	Range [°]	65.9	8.3	68.8	8.2

The sculling angle and the elbow joint angle rise from a minimum of 70–78° (at the beginning of the sculling cycle when initially flexing the forearm) to a maximum of 115–117° (at mid-cycle when extending the forearm) and then decreases to a minimum (at the end of the cycle). The sculling angle (SEF) and the elbow joint angle showed similar temporal characteristics. However, the sculling angle was characterized by a greater range of motion (45° for the SEF angle and 38.7° for the SEW angle for the left upper limb and, similarly, 44.9° for the SEF angle and 39.3° for the SEW angle for the right upper limb) while having at the same time smaller absolute values, i.e., both lower minimum and maximum values, which were due to the different geometry (Fig. 1B) and flexion of the wrist. These differences were found to be statistically significant.

The angle of the wrist joint (EWF) fluctuated around a mean value of 135° of flexion and only slightly changed its position between the minimum and maximum values, from 124–127° to 140–143°, respectively. This range of wrist joint motion was small when compared to other angles, being 16.2° for the left limb and 15.4° for the right limb. It should be mentioned that among the study subjects, some were characterized by a relatively small range of motion of this joint (approximately 10°) while others had nearly twice the range of motion (approximately 20°).

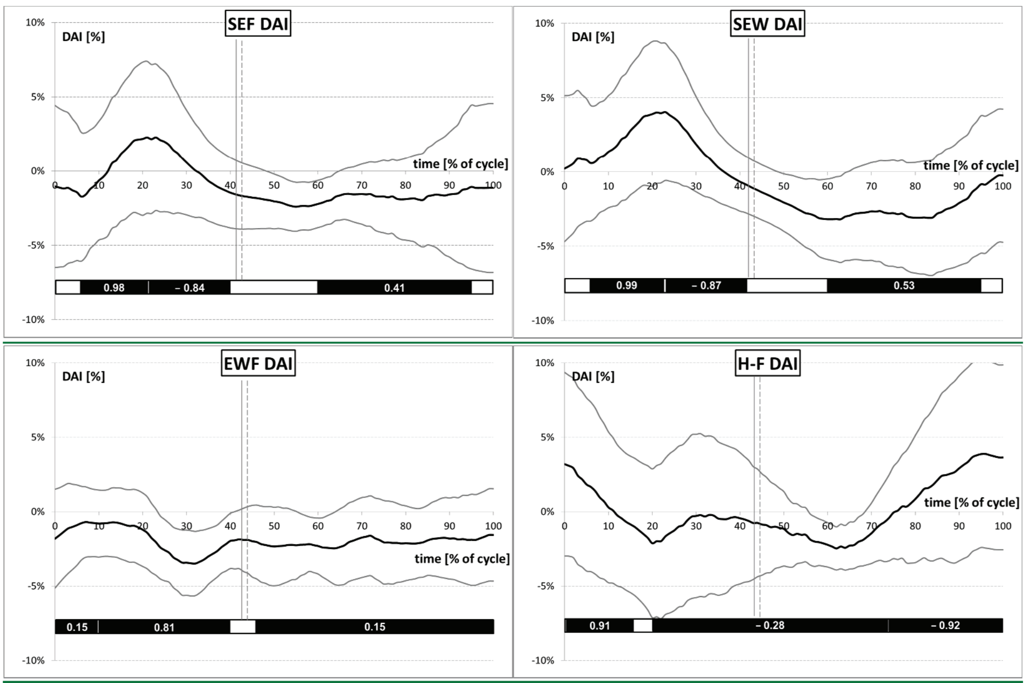

Fig. 3. Dynamical asymmetry index for sculling angle (SEF DAI), elbow flexion-extension angle (SEW DAI), wrist flexion-extension angle (EWF DAI), and arm rotation angle (HF DAI) for the left and right side and averaged over $N = 15$ contestants. The +/– standard deviation (thin line) and the level of linear correlation (Pearson product-moment correlation) between the corresponding angle and DAI value (bottom bar) is also shown in the figure. The two vertical lines designate the left (solid) and right (dashed) sculling phases

The rotation angle of the arm (HF) first decreased (medial rotation of the arm with forearms adducted towards the trunk) from 75–80° at the beginning of the support scull cycle to a minimum value of about 63° at 15% of the cycle duration, and then increased (as the abduction of the forearm from the trunk) to its maximum value of 136° which took place at 65% of the cycle duration, and then again decreased to the minimum value at the start of the next cycle. The range of arm rotation for both the left and right limb was similar and averaged approximately 73°. The rotation of the arms was found to significantly differ in the group of swimmers under study.

The individual differences in the range of motion of the swimmers were even further manifested in magnitude of the asymmetrical movement during support scull. The dynamical asymmetry indexes for the sculling angle (SEF DAI), the elbow joint (SEW DAI), the wrist joint (EWF DAI) and the abduction angle of the forearm (HF DAI) during the support scull movement cycle between the right and left limbs are shown in Fig. 3. In Table 3, the individual results of the distribution of the minimum value (MIN DAI), the maximum (MAX DAI) as well as the range of movement (Range) of the swimmers are presented.

Table 3. Distribution of the minimum, maximum and range of change for DAI and DAI rate of change for sculling angle (SEF), elbow flexion-extension angle (SEW) wrist flexion-extension angle (EWF) and arm rotation angle (HF) for the left and right side and for $N = 15$ contestants

		DAI		DAI Rate	
		mean	±SD	mean	±SD
SEF DAI	Min DAI [%]	–2.4	3.1	–0.4	0.3
	Max DAI [%]	2.3	3.6	0.6	0.3
	Range [%]	4.7	3.0	0.9	0.5
SEW DAI	Min DAI [%]	–3.2	3.2	–0.4	0.3
	Max DAI [%]	4.0	3.5	0.4	0.2
	Range [%]	7.2	4.5	0.8	0.5
EWF DAI	Min DAI [%]	–3.5	2.5	–0.4	0.3
	Max DAI [%]	–0.7	2.2	0.3	0.3
	Range [%]	2.8	3.5	0.6	0.6
HF DAI	Min DAI [%]	–2.5	4.6	–0.5	0.5
	Max DAI [%]	3.9	7.8	0.4	0.4
	Range [%]	6.3	6.6	0.9	0.8

The dynamical asymmetry index of the sculling angle was very similar to those of the elbow joint angle (SEW DAI). While extending the elbow, the mean SEF DAI and SEW DAI were approximately 0% at the beginning of the sculling cycle, which then rose to a maximum value of 2.3% for SEF DAI and 4.0% for SEW DAI at around 20% of the cycle's

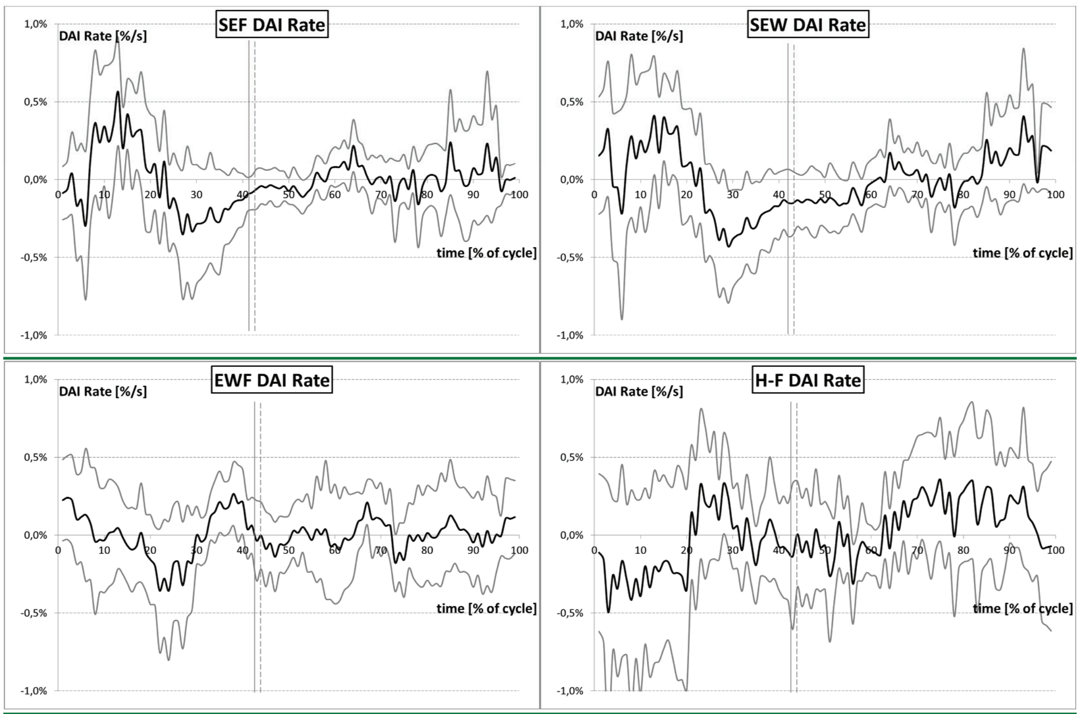

Fig. 4. Dynamical asymmetry index rate of change (DAI Rate) for sculling angle (SEF DAI), elbow flexion-extension angle (SEW DAI), wrist flexion-extension angle (EWF DAI), and arm rotation angle (HF DAI) for the left and right side and averaged over $N = 15$ contestants. The +/– standard deviation (thin line) is also shown in the figure. The two vertical lines designate the left (solid) and right (dashed) sculling phases

duration. When flexing the elbow, the DAI value remained constant (about –2%), decreasing to 0% at the end of the cycle duration. The magnitude of the deviation from the average values indicates a larger diversity of this magnitude among the swimmers.

Analysis of the wrist joint (EWF) asymmetrical movement found a relatively small variation in this measurement. The EWF DAI differed by 2.8% from its minimum value, at –0.7%, to its maximum, at –3.5%. A negative value of EWF DAI in the entire range of motion is associated with the larger value of the EWF angle of the left rather than right hand in most of the test subjects (Fig. 2). Individual analysis of this parameter found a wide variation among the swimmers studied.

The dynamical asymmetry index calculated for the forearm (HF) abduction angle between the left and right limb was found to be highly dynamic. At the beginning of the movement cycle it reached about 3% and then decreased to about –2.5% at 20% of the cycle duration. In the middle of the cycle it decreased even further to approximately 0% (signifying perfectly symmetrical movement) and then increased to about –3% at 65% of the cycle duration. At the end of the sculling movement, the HF DAI decreased to 0% and then increased, becoming positive, to its maximum value of 3.9% at 95% of the cycle duration.

The dynamics of the asymmetry index is best summed up by the rate of change of the dynamical asymmetry index (DAI Rate) as shown in Fig. 4. The figure presents the mean rate of change of the DAI Rate for the sculling angle (SEF), the elbow joint angle (SEW), the wrist angle (EWF) and the arm rotation angle (HF).

The greatest rate of asymmetrical change for SEF DAI and SEW DAI (up to 0.6%/s) was observed at the beginning of the movement phase when extending the elbow joint, while the lowest, of about –0.4%/s, was at around 30% of the cycle duration. When flexing the elbow joint, the mean rate of change fluctuated around 0, which points to only small asymmetrical changes (and no change in the DAI parameter). The range of change of the SEF DAI Rate among the athletes was similar.

The rate of change of the dynamical asymmetry index of the wrist joint (EWF DAI Rate) was comparable to the other joints studied, but had more dynamical changes. At the beginning of the movement cycle, the EWF DAI had a positive rate of change (at about 0.2%/s), and then decreased to where it approached zero (maintaining a constant asymmetric value) at around 20% of the cycle duration. In the next phase, the rate of change rose negatively due to an increase in the EWF DAI parameter, which reached a value of –0.4%/s at 25% of the cycle duration. The rate of change then decreased to zero and subsequently increased positively to a maximum value of 0.3%/s. This rate of change is characterized by an increase in DAI at 35% of the cycle duration. In the second half of the cycle, the asymmetric rate of change fluctuated around zero, which points to a fixed value of asymmetry in this period. As there occurs a small range of variation in the wrist joint angle (EWF DAI) and a large deviation from the mean measured value, the rate of change takes on a quasistatic form.

The rate of change of asymmetry during the arm rotation (HF DAI Rate) at the beginning of the movement cycle changed from having a negative value (on average, about –0.4%/s) in this period, in which the HF DAI value decreased by approximately 0.4%/s, to where it positively increased in value. From 30% to about 65% of the movement cycle duration the asymmetric rate of change decreased and fluctuated around an average value of approximately –0.1%/s. From 65% of the cycle duration to its end, the rate of change of HF DAI increased towards an average value of around 0.35%/s. Similarly, the HF DAI Rate varied between the swimmers under study.

4. Discussion

Maintaining the body balanced under water, in an inverted position (head down) is a very difficult task for synchronized swimmers. This is evidenced by the fact that the acquisition of the necessary skills to do so takes about two years. It is assumed that one of the conditions to properly perform this technique is having the upper limbs perform symmetrically during support scull, which allows a swimmer to extend their legs out of the water as far as possible while keeping balance for a significant period of time. One of the difficulties in performing this technique stems from the fact that humans are naturally asymmetric in nature (Szpala et al., 2005). This is manifested not only in the asymmetric arrangement of our internal organs, but also in the natural asymmetry of human movement. As found in the available literature, studies on asymmetry focused solely on the relative differences between the individual values of specific movements between the right and left side of the human body (Mastalerz and Urbanik [18]; Aujouannet et al. [2]).

Research revealed that asymmetry is found in the kinematic and kinetic parameters of the limbs during gait (Winiarski [26]; Michalski et al. [19]), in studies of the effects of muscle strength on the right and left side of the body (Rutkowska-Kucharska et al. [23]; Szpala et al. [24]), as well as in the rhythm and precision of certain movement by the right and left upper limbs (Jaszczak [14]; Riley et al. [20]; Jaszczak and Zatoń [15]) did make use of the concept of dynamical asymmetry, however, his study made reference to it only as a singular value obtained by the differences in the pressure distribution of the hand during the propulsion phase in breaststroke swimming. So far, no study has been found which focuses on asymmetry as a parameter of an entire range of motion (dynamical asymmetry) or designating in which areas there are significant instances of symmetry and asymmetry.

This study presented a method for evaluating the symmetry of the limbs movement during support scull in the vertical position as a facet of synchronized swimming. In examining the range of motion during the entire movement cycle, two critical aspects were determined: the dynamical asymmetry index as well as the rate of change of the DAI when a swimmer lost and then recovered symmetrical movement. Using the dynamical asymmetry index (DAI) proposed, in combination with the rate of change it underwent (DAI Rate), one can find asymmetry in the support scull movement across the entire duration of sculling in the group of swimmers under study.

As mentioned, the DAI describes the nature and magnitude of the asymmetry and indicates the direction of the asymmetry. A positive DAI value indicates a higher level of asymmetry for the left, while a negative value for the right side. The DAI Rate describes the rate in which symmetry is lost or restored. A large or small positive value of the DAI Rate indicates whether there is a fast or slow increase in the asymmetry factor, while a small or large negative value indicates a fast or slow reduction of asymmetry.

As was found by compound correlation analysis, the magnitude of movement asymmetry and the magnitude of its rate of change depended on the range of motion of the individual joints. A strong correlation was found between the sculling angle (SEF) and elbow joint angle (SEW) at the beginning phase of extending the elbow, where an increase in the angle had the asymmetry value also rise, with the average rate of change being 0.17%/s. In the final phase of extending the elbow, a decline in the DAI was observed at an average rate of approximately –0.23%/s. Between 40% and 60% of the cycle duration, the sculling angle did not change and its DAI only slightly increased in the negative value (a direction change of asymmetry). When flexing the limbs, the sculling angle decreased along with a decrease in the negative DAI value (at an average rate of change of 0.03%/s).

The angle of the wrist joint (EWF) was much lower than in the range of motion of the other joints. A linear correlation analysis showed that an increase in the EWF angle (dorsiflexion of the hand) was coupled with an increase in asymmetry. During the time period at around 45% of the cycle duration and reaching up to 10% of the next cycle, the EWF angle decreased and with it was a slow decrease in the negative value of the EWF DAI at a rate of 0.01%/s. During the rotation of the arm (HF angle), in the first 15% of the cycle duration, the HF DAI value quickly decreased to zero at an average rate of –0.27%/s. However, this state of perfect symmetry did not last for long. When the arm entered the external rotation phase (at 20–75% of the cycle duration, where the HF angle increases), the asymmetry value changed and several times alternately increased and decreased while being negative and slow approached towards zero. As a result, the change in the asymmetry factor in relation to the change in the angle is poorly negatively correlated. During the final phase of rotation, the HF DAI increased, which reveals an increase in asymmetry.

Positive correlation was found between the aggregated results of the DAI and the asymmetry rate of change (DAI Rate) throughout the entire range of motion, which means that the greater the extent of the changes of asymmetry in sculling, the greater the asymmetric rate of change. No correlation was found between the DAI values of the individual joints and the change in the DAI Rate. The asymmetry of sculling was found to be influenced by the asymmetry of arm rotation (HF angle), the elbow joint (SEW angle) and the wrist joint (EWF angle). The magnitude of asymmetry of the sculling angle (SEF) was dependent on the asymmetry of movements of the elbow and wrist joints. The asymmetry of support scull was also influenced by another factor as found by the markers on the head and pubic symphysis, which are considered to be in phase due to the rigidity of the human body segments connecting these two points. The marker on the head traveled a greater distance in the vertical direction than the marker on the pubic symphysis, which can point to corrective head movements in order to maintain balance. However, no statistically significant differences were found in the displacement between these two markers in any of the movement components of sculling.

Some limitations of the study stem from the difficulty of filming underwater, which required that the study be limited to analysis of selected body movements only. Joining two two-dimensional images into one three-dimensional created a kind of pseudo-three-dimensional space, which could have caused measurement errors. The recording frequency could have also had an effect on the results. Support scull has a very short cycle (a duration of approximately 0.7–1.0 second), while the DAI Rate was calculated numerically using the differential quotient and was dependent on the sampling frequency of the cameras and regression method that was used in this study (which changed the characteristics of the sampling time). This is manifested by the presence of low-frequency changes in the DAI Rate. Further smoothing of the measured DAI movements or noise filtration could improve the quality of the results.

5. Conclusions

The use of the dynamical asymmetry index (DAI) to assess the symmetry of the support scull movement while maintaining balance in the inverted position indicates its practicality in evaluating technique in synchronized swimming. Analysis of the dynamical changes of movement symmetry could provide coaches with information about the parameters critical in performing support scull, whose variability is associated with a swimmer's effectiveness in executing the inverted position.

The concept and evaluation method of the dynamic asymmetry in movement as was used in this study is not the same as the concept of dynamic asymmetry that is used to describe the asymmetry of kinematic and kinetic parameters of human movement (Jeka and Kelso [16]). The advantage of our approach in assessing movement asymmetry lies in the fact that the method outlined in this study does not limit one to only state the existence of movement asymmetry, but evaluate and assess the dynamics of this movement asymmetry.

The Dynamical Asymmetry Index (DAI), used in this study for measuring kinematic parameters, is a good indicator of asymmetry found throughout the entire range of motion of the upper limbs an the DAI's rate of change (DAI Rate), calculated as a time derivative of the DAI, is a measure of the rate of change of symmetry and is an indirect measure of the speed of losing balance.

Acknowledgements

This study was made possible by the financial support of the Polish Ministry of Science and Higher Education (Grant No. 0338/B/P01/2010/39).

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