Accelerometer profile of motion of the pelvic girdle in butterfly swimming

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Purpose: The aim of the study was to develop a method to measure and analyse kinematics of movement of the pelvic girdle in butterfly swimming in order to support training of technical skills. *Methods:* A device for recording triaxial accelerations and triaxial rotational angular velocities was mounted on the dorsal part of the pelvic girdle of athlete. The measurements were performed in ten elite butterfly swimmers (age: 23.1 ± 3.7 years, body height: 187.6 ± 4.3 cm, body mass 83.4 ± 6.33 kg). The task of the athlete was to swim one length of short course pool at maximal intensity. Individual mean graphical and numerical profiles of the kinematics of the movement of the pelvic girdle was computed, within the average cycle based on five consecutive cycles. *Results:* Statistical analysis of numerical individual parameters of profiles of the athletes studied revealed statistically significant differences between the swimmers. Statistically significant correlations were also found between personal best times in 50 m swimming ($r = -0.76$, $p < 0.05$) and 100 m swimming ($r = -0.76$, $p < 0.05$) and duration of the part of the cycle connected with the decline in velocity from maximum translational motion velocity obtained during propulsion with the upper and lower limbs to minimum value of the velocity obtained before the beginning of propulsion only with the lower limbs. *Conclusion:* The proposed measurement method, presentation and analysis of the profile of the pelvic girdle motion in butterfly swimming represents a good tool for fast and effective qualitative and quantitative biomechanical evaluation of movement technique components.

Key words: swimming, butterfly swimming, acceleration, velocity, profile of pelvic girdle motion

1. Introduction

The key role in the research on biomechanics of swimming and in sports practice is played by cinematographic analyses [3], [4], [11], [14], [15]. Precise video analyses are performed using high-quality video cameras in dedicated swimming pools. They require participation of experienced operators and performing tedious analyses [3]. Results of video analyses, especially those concerning changes in velocities and accelerations, are substantially smoothed and do not enable capturing of subtle differences in the movement technique. Causes of smoothing curves of changes of speed and acceleration, studied by analysis of video are: positioning errors on the body of the player of the selected point or marker, a relatively low frequency of write video frames, and the need to apply path differentiation method to calculate the speed and double the differentials for the calculation of acceleration.

Apart from the cinematographic methodologies of measurement of movement velocity, swim speedometer systems have been also used, with swimming velocity measurements evaluated based on the velocity of unwinding the rope attached to the swimmer's belt [2], [4], [9]. The limitations of this method include the opportunities of performing measurements for only one length of a short course pool, additional load to the swimmer's body caused by the force needed to develop and maintain the necessary rope tension and opportunities of collision of the rope with the swimmer's limbs [2].

Accelerometers and gyroscopes have been increasingly used for motion analysis. Attached to se-

lected segments of swimmer's body, they enable the analysis of motion kinematics for selected body segments, e.g., wrist [8], pelvic girdle or body trunk [5], [12]–[14], or many body segments, simultaneously using special suits that stabilize fixation of the sensors [6], [7]. Compared to the cinematographic method, right software for processing of the data from accelerometers helps obtain information about the swimmer's movement technique in the basic training in an easier, faster and cheaper manner. Direct measurement of the acceleration and speed changes by accelerometer method is much more sensitive than video analysis method, especially in the case of analysis of root cause of local disorders of fluency of the motion.

In the case of general analysis of swimmer's movement technique, especially of that concerning changes in velocity of motion within a single cycle, analysis of motion kinetics of the centre of mass or the point near the centre of mass seems to be purposeful. Located near the centre of mass, the pelvic girdle is a body segment that transfers mutual effects of lower limbs and upper limbs through upper body, with mutual synchronization of activities defining the movement technique. From the standpoint of measurements, dorsal part of the pelvic girdle represents an optimal location for fixation of the measurement recording device [7], [13], [14] in a manner that does not disturb individual movement technique, especially in butterfly swimming.

Based on video analysis, in butterfly swimming style mainly the relationship between the arm-leg coordination and the sports result [3], [15] and the relationship between the intra cycle velocity amplitude and sports results [2], or the energy cost of effort are examined [1]. Based on accelerometer measurements, mainly the relationship between technique and shape of curve of acceleration and velocity of selected segments of the body in the swimming cycle are examined [7].

The aim of the study was to develop a method to measure and analyse kinematics of movement of the pelvic girdle in butterfly swimming in order to support training of technical skills.

2. Material and methods

Participants

The study examined ten male elite butterfly swimmers (age: 23.1 ± 3.7 years, body height: 187.6 ± 4.3 cm, body mass: 83.4 ± 6.33 kg, personal best times swimming on the long pool for 50 m distance: 24.83 ± 1.21 s and for 100 m distance: 54.51 ± 2.54 s).

Measures

The profile of the cyclic motions obtained by using measured data by triaxial gyroscope and triaxial acceleration is further termed AG3DC profile. Measurements of the AG3DC profile were performed according to the methodology described for the breast-stroke swimming style in a study by Staniak et al. [13]. An integrated recording device was used for the measurements (REJ006, JD Jarosław Doliński, Poland) with in-built triaxial accelerometer and triaxial gyroscope. The device, with the dimensions of $65 \times 50 \times 30$ mm and mass of 150 g, was placed in lightweight stiff foam formed in a manner that minimizes hydrodynamic resistance and ensures a stable fixation on the dorsal portion of the pelvic girdle of the swimmer (Fig. 1). The centre of the recording device was located at the height of the beginning of the sacrum bone. The recording device with the foam was fixed with a special belt made partly as an elastic band and partly as an inextensible rope. The elastic part of the belt is used around the underbelly of the examined athlete.
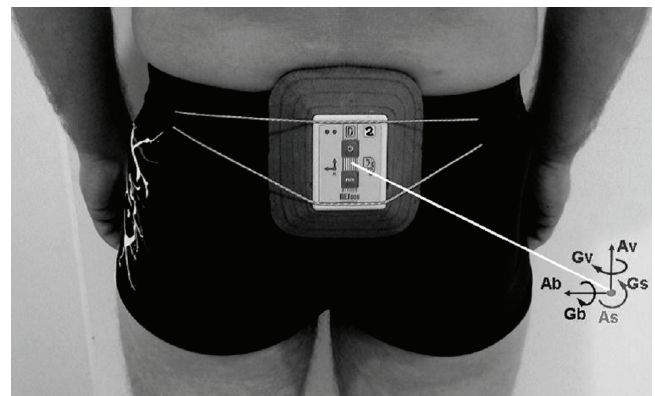

Fig. 1. Method of fixing and the layout and orientation of the measurement axes of the device for direct recording of triaxial accelerations and angular velocities of rotation. Notes: acceleration components: *Av* – along the vertical axis, *Ab* – along the transverse axis, *As* – along the sagittal axis) and components of angular velocities of rotation: *Gv* – around the vertical axis, *Gb* – around the transverse axis, *Gs* – around the sagittal axis of swimmer's body

We directly measured the acceleration components (*Av* – along the vertical axis, *Ab* – along the transverse axis, *As* – along the sagittal axis) and components of angular velocities of rotation (*Gv* – around the vertical axis, *Gb* – around the transverse axis, *Gs* – around the sagittal axis of swimmer's body, actually connected with the system of reference, with respect to the casing of the recording device).

The acceleration was measured over the measurement range of ± 6 g using a low-pass anti-aliasing filter

with cut-off frequency of 292 Hz. The angular velocity of rotation was measured over the measurement range of ±500 deg·s^{-1} using a low-pass anti-aliasing filter with cut-off frequency of 93 Hz. The values measured were sampled with the frequency of 400 Hz.

Measurement accuracy for the acceleration components was verified at static condition with respect to the gravitational acceleration. The absolute measurement error for acceleration was ±0.2 m/s^{-2}. Measurement accuracy for angular velocities of rotation was verified indirectly based on the measurement and calculation of the angle of rotation of the recording device within the range of 90 degrees around each axis. Absolute error of angle calculation was ±1 deg. Absolute error of measurement for angular velocity of rotation was 0.6 deg·s^{-1}.

In order to identify time of characteristics points of the profile measured with respect to configuration of swimmer's limbs, swimming was recorded using two HDR-A200V (Sony, Japan) cameras placed in a watertight casing and fixed to a dedicated truck moved manually on the swimming pool edge parallel to the swimming direction. One of the cameras was located 0.5 m under the water surface whereas the other was 0.5 m over the water surface.

Recording from both cameras was synchronized and connected into one file. Video recordings were processed by means of the Kinovea (www.kinovea.org) software. Accuracy of recording synchronization from cameras was $\pm$ one frame. Frame rate was 120 frames per second; therefore, camera synchronization accuracy was $\pm$ 0.0083 s.

The mechanical method was used to synchronize video recordings with profiles of changes in accelerometer signals of the recording device. Accuracy of synchronization of video recordings with the accelerometer recordings determined video recording speed and was ±0.0083 s.

Procedures

Ethical approval for this study was provided by the Local Ethical Committee at the Institute of Sport – National Research Institute, Warsaw, Poland. A written informed consent was obtained from each participant. The study was conducted in accordance with the Declaration of Helsinki.

Measurements were performed during swimming in a 25 m swimming pool, with the exercise level near the maximal exercise adequate for current training microcycle. The athletes jumped from the starting platform, swimming over one length of the swimming pool using the butterfly stroke including the butterfly swimming turn. Individual warm-up was performed by athletes before the measurement. The measurements were performed in various training microcycles. In total, individual measurements of ten elite athletes were analysed.

Triaxial components of accelerations *Av*, *Ab*, *As* and triaxial components of angular speed of rotation *Gv*, *Gb*, *Gs*, connected, nearly with anatomical axis of subject body, are measured directly. Based on the above data the software calculates the changes in acceleration (*Ax*) and the changes in velocity (*Vxr*) of translational motion in the axis parallel to the water surface. The components of the acceleration (*Ax*) and of the velocity (*Vxr*) are further termed as the acceleration and the velocity of translational motion. Components of vertical acceleration (*Az*) in the axis perpendicular to the water surface and changes in the angular velocity (*Gy*) and the angle of inclination (*KGy*) of the pelvic girdle with regard to the transverse axis of the swimmer's body are also calculated. The center of the new coordinate system 0xyz is still connected to the sacrum near the center of the recorder.

The profiles measured were smoothed with the low-pass, four-pole Butterworth filter with cut-off frequency of 20 Hz. The cut-off frequency of the filter was selected using the assumption that the calculated amplitude of changes in translational motion velocity should not be damped by more than 0.5% as an effect of filtering of the signals measured. Furthermore, the collapses of the acceleration profiles, which are critical from the standpoint of motion analysis, will be well noticeable.

Of swimming cycles typical of butterfly stroke for each athlete, we chose five consecutive cycles from which individual graphical profile of the cycle of profiles of measured and calculated values was determined. Mean numeric profile for the cycle containing arithmetic means of selected values, characteristic points of the analysed profiles and mean values and standard deviations of the relative (with respect to cycle duration) times to reach these values measured from the beginning of the cycle were also calculated. These values are further termed numeric as parameters of the profile. The profile obtained was termed AG3DC profile. The profile was computed using the author's software STA1v0 (Zbigniew Staniak, the Institute for Sport – State Research Institute, Poland).

Statistical analysis

Distribution of all the analysed variables was assessed by the Kolmogorov–Smirnov test and all of them had normal distribution. The individual profiles of athletes were compared using one-way analysis of vari-

ance (ANOVA). Significance of differences in means was verified using the *post-hoc* Fisher's LSD test. Pearson's correlation coefficient was used to evaluate correlations between all parameters. For the statistical analyses, the value of $\alpha = 0.05$ was considered as significant. All computations were performed with STATISTICA software (v. 12.0, StatSoft, USA).

3. Results

An example of individual AG3DC profile for the movement of the pelvic girdle in butterfly swimming is presented in the diagram in the rectangular coordinate system (Fig. 2). The vertical axis of the diagram represents normalized values of profiles. The profiles were normalized with respect to the referential values for each value. The referential values are presented in the left lower corner of the diagram.

Horizontal axis of the diagram expresses mean duration of the swimming cycle expressed in percentage terms. The beginning of the cycle was adopted as the point at which the profile of the angular velocity of

rotation (Gy) of the pelvic girdle around the transverse axis of swimmer's body changes the sign from negative to positive in the part of the cycle connected with the beginning propulsive arm activity. At this point, the angle of pelvic girdle inclination (KGy) has a minimal value and then starts to increase towards the maximal position.

With respect for other local extremes of changes in translational motion velocity (Vxr), the swimming cycle was divided into four characteristic phases connected with acceleration and deceleration of the translational motion of the pelvic girdle similar as in breaststroke swimming [13].

The first phase of the cycle (*upper limb propulsion, with lower limb propulsion in the further part*), denoted as vALP, starts at the instant of obtaining the minimal value of velocity ($\min Vxr_{vALP}$) and ends at the moment of obtaining the first extreme of translational motion velocity ($\max Vxr_{vALP}$). An increase in velocity begins with the instant of the effective pulling movement of the upper limbs. The maximum velocity ($\max Vxr_{vALP}$) is achieved before the completion of the second kick with lower limbs and before removing hands from water upon completion of the arm push phase.
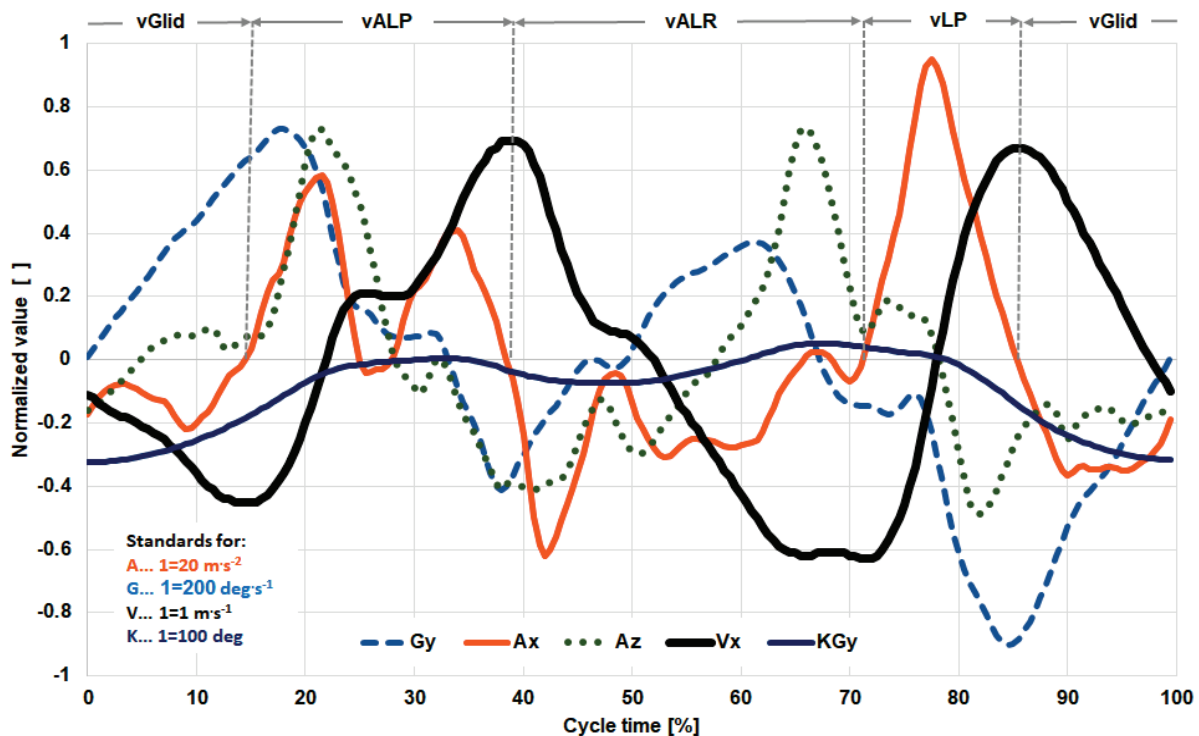

Fig. 2. Example of AG3DC profile of the pelvic girdle motion for the average cycle of butterfly swimming.
Notes: *Ax* – horizontal acceleration of translational motion, *Az* – vertical acceleration of translational motion,
Vxr – change in translational motion velocity, *Gy* –angular velocity of pelvic girdle inclination around the transverse body axis,
KGy – angle of pelvic girdle inclination, *v*ALP – part of propulsive activity of the upper and lower limbs,
*v*ALR – part of motion deceleration connected with completion of propulsive activity with lower and upper limb
and moving upper limbs forward and bending lower limbs, *v*LP propulsive part connected with propulsive activity of lower limb,
*v*Glid – part of movement deceleration connected with driving the hands into water and gliding

The second phase of the cycle (*motion decelera-tion*), denoted as *v*ALR, begins at the point of reaching the first local maximum for translational motion velocity (maxVxr_{vALP}) and ends at the point of reaching the minimum of translational motion velocity (minVxr_{vLP}). A decline in velocity starts before the end of the second kick and before the removal of hands from water. Velocity minimum (minVxr_{vLP}) generally occurs at the instant of the beginning of the motion of the first kick with lower limb.

The third part of the cycle (*part of lower limb propulsion*), denoted as *v*LP, starts at the moment of reaching the minimum of translational motion velocity (minVxr_{vLP}) and ends at the point of reaching the last local maximum of translational motion velocity (maxVxr_{vLP}). An increase in velocity begins with the beginning of the first kicking motion and ends before the end of the first kick.

The fourth phase of the cycle, denoted as *v*Glid (*gliding phase*), begins at the point of reaching the second local maximum for translational motion velocity (maxVxr_{vLP}) and ends at the point of reaching the minimum of translational motion velocity (minVxr_{vALP}). A decline in velocity begins before the end of the first kick and ends at the point of effective propulsive pulling with upper limbs.

Tables 1 and 2 present mean values and standard deviations (±SD) for selected numerical parameters of the AG3DC profile of average cycle that describe changes in translational motion velocity of the pelvic girdle obtained by athletes analysed in our the study: mean rate SR = 55.59 ± 4.11 s·min^{-1} (cycles per minute). Mean fluctuation of translational motion velocity (meanVxr) was 0.59±0.11 m·s^{-1}. Peak-to--peak fluctuation of translational motion velocity in the cycle (ptpVxr_c) was 1.34 ± 0.20 m·s^{-1}, peak-to--peak fluctuation of translational motion velocity in the first phase of the cycle was ptpVxr_{vALP} = 1.22 ± 0.13 m·s^{-1}, and peak-to-peak fluctuation of translational motion velocity in the third phase of the cycle was ptpVxr_{vLP} = 0.99 ± 0.30 m·s^{-1}. The dimensionless index rytmV, calculated as a quotient of the time at which the velocity of the propulsive motion is equal or greater than the mean value in the cycle, was 0.94 ± 0.15. Mean values of the above-mentioned parameters, calculated from five cycles for individual profiles of the athletes studied, differed statistically significantly.

Figure 3 presents the profiles of fluctuation in translational motion velocity (*Vxr*) versus normalized to 100% duration of the cycle from individual profiles of the athletes studied.

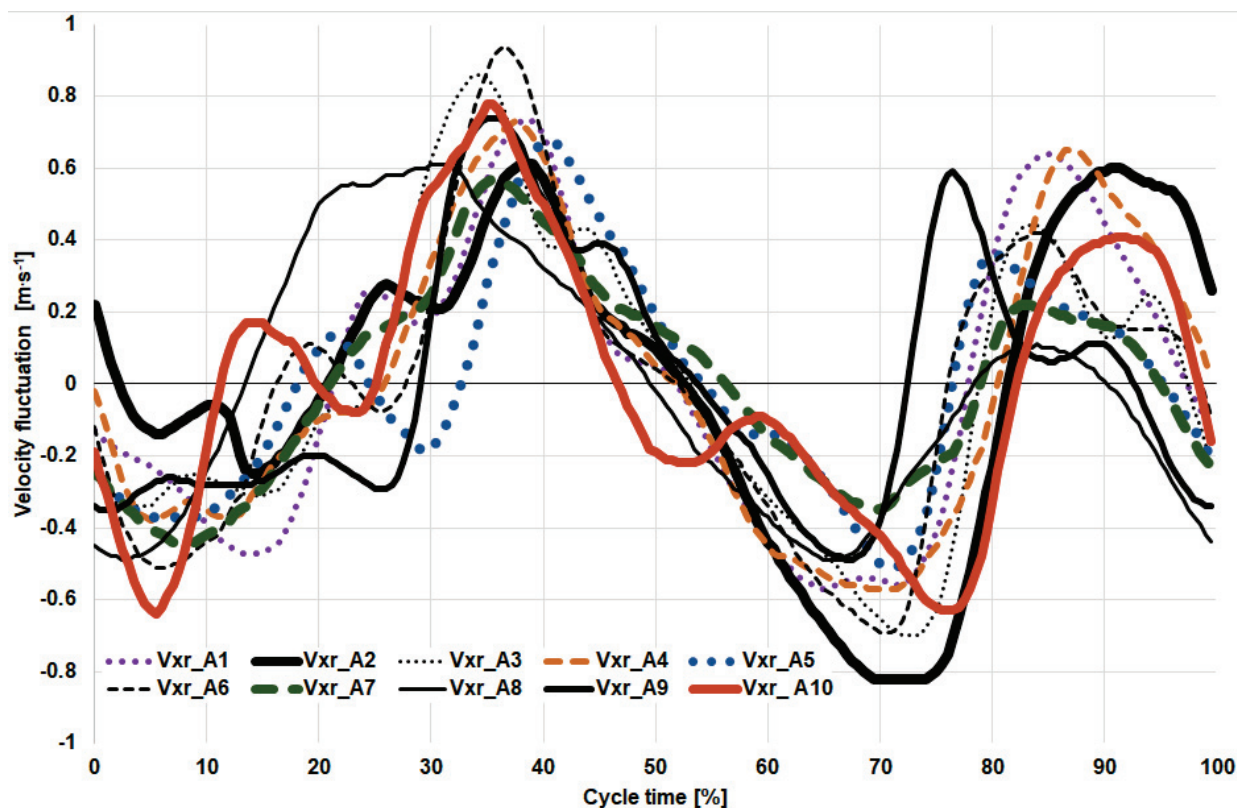
Fig. 3. Mean profiles of fluctuation of translational motion velocity for the athletes in the cycle.

Notes: *Vxr* – profile of fluctuation of translational motion velocity with respect to average velocity in the cycle, A1÷A10 – athletes' numbers

Table 1. Mean values (±SD) of selected parameters of the profile for consecutive characteristic cycle phases

$n = 10$	vALP	vALR	vLP	vGlid
RTD [%]	27.7 ± 2.7	34.0 ± 3.7	14.2 ± 2.8	24.1 ± 4.8
meanAx [m·s^{-2}]	4.27 ± 0.93	−3.63 ± 0.80	6.99 ± 2.58	−4.00 ± 1.33
maxVxr [m·s^{-1}]	0.76 ± 0.10	–	0.44 ± 0.20	–
RTO_maxVxr [%]	37.3 ± 3.6	–	85.5 ± 3.2	–
minVxr [m·s^{-1}]	−0.47 ± 0.09	–	−0.55 ± 0.14	–
RTO_minVxr [%]	9.5 ± 3.9	–	71.2 ± 3.3	–
maxAx [m·s^{-2}]	13.8 ± 3.9	–	15.4 ± 5.6	–
RTO_maxAx [%]	28.1 ± 7.4	–	79.2 ± 3.0	–
minAx [m·s^{-2}]	–	−11.6 ± 4.7	–	−8.6 ± 3.0
RTO_minAx [%]	–	33.0 ± 9.4	–	96.1 ± 2.9
maxAz [m·s^{-2}]	12.0 ± 3.5	–	9.84 ± 3.0	–
RTO_maxAz [%]	20.5 ± 3.6	–	68.7 ± 4.2	–
minAz [m·s^{-2}]		−8.9 ± 2.0	–	−7.2 ± 3.0
RTO_minAz [%]		38.2 ± 3.1	–	84.1 ± 7.1
maxGy [deg·s^{-1}]	180.5 ± 42.5	–	56.0 ± 23.5	–
RTO_maxGy [%]	18.3 ± 4.2	–	61.5 ± 6.1	–
minGy [deg·s^{-1}]	–	−99.4 ± 58.0	–	−209.3 ± 49.4
RTO_minGy [%]	–	37.1 ± 4.7	–	85.9 ± 3.5

Notes: vALP, vALR, vLP, vGlid – individual specific phases of the cycle; RTD – relative duration of the cycle phase; meanAx – mean value of acceleration of translational motion in a cycle phase; maxVxr, minVxr – maximal and minimal value of the fluctuation of translational motion velocity with respect to mean velocity in the cycle; RTO_maxVxr, RTO_minVxr – relative time to maximal and minimal value of the fluctuation of translational motion velocity; maxAx, minAx – maximal and minimal value of the acceleration of translational motion; RTO_maxAx, RTO_minAx – relative time to maximal and minimal value of the acceleration of translational motion; maxAz, minAz – maximal and minimal value of acceleration of the vertical motion; RTO_maxAz, RTO_minAz – relative time to maximal and minimal value of the acceleration of the vertical motion; maxGy, minGy – maximal and minimal value of angular velocity of inclination of the pelvic girdle; RTO_maxGy, RTO_minGy – relative time to maximal and minimal value of angular velocity of the pelvic girdle inclination.

Table 1 presents mean values (±SD) of selected parameters of profiles for individual parts of the swimming cycle for the athletes studied. Mean values of the parameters contained in Table 1, calculated from five cycles for individual profiles of the athletes studied, differed statistically significantly.

Local extremes of the values of the profile of fluctuations in translational motion velocity (Vxr) are observed at the ends of each of the four phases of the cycle. Local extremes of the value of acceleration (Ax) of translational motion occur within each characteristic phase of the cycle. Local extremes of the values of vertical acceleration (Az) and angular velocity of the pelvic girdle inclination (Gy) are mainly observed in the range or close near the indicated cycle phases.

Table 2 shows statistically significant Pearson's correlation coefficients for the correlation of the best times in 50 m swimming (BT50) and best times in 100 m swimming (BT100) and values of numeric parameters of the AG3DC profile of the swimming cycle.

Table 2. Values of statistically significant Pearson's correlations for parameters of the profile with best times obtained by the athletes in 50 m and 100 m swimming

$n = 10$	BT100	RTD$_{v\mathrm{ALR}}$	RTO_min$Gy_{v\mathrm{LP}}$
BT50	0.97*	−0.76*	−0.77*
BT100	1.00	−0.73*	−0.70*

Notes: BT50 – best time in 50 m swimming; BT100 – best time in 100 m swimming; RTD$_{v\mathrm{ALR}}$ - relative duration of the second cycle phase; RTO_min$Gy_{v\mathrm{LP}}$ – relative time to minimal value of the angular velocity of inclination in the third specific cycle phase; * –$p < 0.05$.

4. Discussion

The statistically significant high value of the correlation coefficient ($r = 0.97$) between the best 50 m and 100 m swimming times (BT50, BT100) obtained in a long course pool suggests that sports performance of the athletes studied could be largely dependent on movement technique.

The shape of profiles of fluctuations in translational motion velocity (*Vxr*) of the pelvic girdle is, in general, similar to the profiles presented in the literature [2], [4]. The charts illustrate noticeable characteristic collapses of the profiles of velocity changes connected with coordination of athlete's body segments in, e.g., the first phase of the cycle (*v*ALP) and the second phase of the cycle (*v*ALR). In this group of athletes, mean value of peak-to-peak fluctuations of velocity in the cycle (ptp*Vxr_c*) is similar to the value presented in the charts in the literature [2], [4], obtained using the methods of video analyses or using the method of unwound rope.

A plethora of studies have used video analysis to determine the duration of individual parts of the cycle in order to establish coordination correlations between activities in upper and lower limbs in butterfly swimming [3], [10], [15]. Analysis of durations of individual cycle phases was referred to the values presented in the literature [3] for V50 efforts of elite swimmers, who reached the mean swimming rate of (SR = 53.3 ± 2.6 s·min⁻¹), similar to the rate observed in the athletes in our study (SR = 55.7 ± 3.8 s·min⁻¹).

In our study, relative duration of the first phase of the cycle (RTD$_{v\text{ALP}}$ = 27.7 ± 2.7%), which determined the effective propulsion with upper and lower limbs, should be compared with the total of duration of the phases of the cycle connected with the first part of the propulsive activity of the upper limbs (Pull phase = 24.4 ± 4.4%) and the second part of the propulsive activity of the upper limbs (Push phase = 22.1 ± 2.8%). The difference of 19.4% is substantial. This results from the fact that the beginning of activity of the pull phase of the upper limb movement is aimed to lift the body, whereas the propulsive effect in the form of increasing the translational velocity (*Vxr*) from minimal value occurs much later with respect to the beginning of the motion of the pull phase of the upper limb movement. This delay is, in general, equal to the time of obtaining minimal translational motion velocity with respect to the beginning of the cycle (RTO_min*Vxr*$_{v\text{ALP}}$ = 9.5 ± 3.9%). Furthermore, the final part of the arm push phase and the final part of the leg second kick occurs substantially (up to 10% of cycle time) after reaching maximal velocity max*Vxr*$_{v\text{ALP}}$. These delays are noticeable in video recordings synchronized with the profiles of accelerations of the analysed races.

Mean duration of the second phase of the cycle (RTD$_{v\text{ALR}}$ = 34.0 ± 3.7%) determines the relative duration of motion deceleration, when the athlete performs the second phase of the second kick, the second upper limb push phase and moves the upper limbs forward while bending the lower limbs before the first kick. This time should be actually equal to the duration of the lower limbs movement from the lowest position after the second kick to the highest position before the first kick, referenced by Chollet [3] as time duration of the "2 upward undulation" (2 upward undulation = 29.6 ± 4.1%). The 4.4% difference is expected since the end of the second kick observed in video recordings occurs after reaching a maximal velocity max*Vxr*$_{v\text{ALP}}$.

Mean duration of the third phase (RTD$_{v\text{LP}}$ = 14.2 ± 2.8%) connected with effective propulsion of the first kick should be equal to the time of leg extension during the first kick (1 downward undulation = 17.5 ± 1.7%). The 3.3% difference is also expected since the end of the first kick observed in video recordings occurs after reaching a maximal velocity max*Vxr*$_{v\text{LP}}$.

The literature reports on duration of the fourth (last) cycle phase (RTD$_{v\text{Glid}}$ = 24.1 ± 4.8%) connected with the return of the lower limbs to the level after the first kick and the beginning of the "catching" the water with the upper limbs, are still inconclusive as this phase includes the end of the catch phase and the beginning of the pull phase.

Smoothness of the profile of changes in translational motion (*Vxr*) depends on coordination of athlete's body segments that generate propulsion. The study [3], which referred to butterfly swimming, found that, contrary to common opinion, effective butterfly swimming does not require much strength. Rather, adequate arm-leg synchronization is needed. The parameters of arm-leg coordination were also identified: T1, T2, T3, T4, which determined relative time between consecutive characteristic extreme points of activity of upper and lower extremities. In our study, they are represented by local collapses of profiles of changes in velocity (*Vxr*) or acceleration (*Ax*). A direct comparison of the values of coordination parameters from the study [3] (T1÷T4) with time duration of characteristic collapses of curve of *Vxr* of AG3DC profiles seems to be pointless since in extreme positions of arms or legs propulsive efficiency is usually low. However, the conclusions can be drawn on arm-leg coordination in the context of propulsive effectiveness in the cycle phases that contain local disturbances of smoothness of profiles of changes in translational motion velocity (*Vxr*).

A typical collapse of the increase in the profile of translational motion velocity (*Vxr*) observed in the central part of the first cycle phase (*v*ALP) can be linked to the coordination parameter T3. This collapse results from low propulsive efficiency of arms in the phase of transition from the pull to push motion,

which decelerates the movements of the lower limb bending to the initial position before the second kick and arm and leg coordination.

An insignificant collapse in the dynamics of the decline in the profile of translational motion velocity (*Vxr*) often observed in the first part of the second cycle phase (*v*ALR) can be linked to the coordination parameter T4. Among other things, this collapse is attributable to coordination between the arms in the phase of removing the hands from water and legs in the final part of the second kick.

A flat or sharp shape of the profile of translational motion velocity (*Vxr*) in the last part of the second (*v*ALR) cycle phase can be linked to the coordination parameter T1. The shape of the profile depends on: dynamics of arm forward thrust, dynamics of the final phase of the upper limb bending movement that precedes the first kick and coordination between the upper and lower limbs.

The shape of the profile of translational motion velocity (*Vxr*) in the last (*v*Glid) phase of the cycle can be linked to the coordination parameter T2. The shape of the profile depends on the arm and leg coordination and the direction of the propulsion connected with water catching.

Correction of arm-leg coordination can be useful in improving the smoothness of profile of changes in translational motion velocity (*Vxr*) and propulsive effectiveness in each of the above mentioned cycle phases.

Statistically significant negative values of correlation coefficients for best swimming time in a long course pool (BT50 $r = -0.76$ and BT100 $r = -0.73$) and relative duration of the cycle phase RTD_{vALR} show that the athletes studied for whom relative duration of this cycle phase is longer obtain better sport results. This suggests the purposiveness of the emphasis on smoothness and avoiding the excessive dynamics during performance of the second part of the kick, second part of the push phase, first part of transition of hands over the water surface and bending the lower limb before the first kick. This correlation is also consistent with the recommendation for performing a long second kick [9] and with the recommendation for long air arm recovery phase [15], determined by the Fly-arm indicator.

The relative duration of the second (*v*ALR) phase of the cycle can be also elongated by shortening of the relative duration of other cycle phases, especially the last one (*v*Glid) and the first one (*v*ALP). Shortening of the gliding phase for sprint butterfly is recommended by Strzała [15]. One of the factors that determine duration of arm-leg propulsion cycle phase (*v*ALP) is synchronization of the movements of upper and lower limbs during completion of arm-pull and transition to the push phase and beginning of the second kick. Excessive delay results in disturbed smoothness of the increase in acceleration (*Ax*) and velocity (*Vxr*) of translational motion through unfavourable extension of the duration of this cycle phase (*v*ALP). These observations are supported by a low value of T3 parameter of arm-leg synchronization in advanced athletes demonstrated by Seifert and co-authors [10].

A statistically significant negative value of correlation coefficient for the relationships between the best swimming time in a long course pool (BT50 $r = -0.77$ and BT100 $r = -0.70$) and relative time of local minimum of angular velocity of the pelvic girdle inclination RTO_minGy_{vLP} is a consequence of the above-discussed relationships.

No statistically significant correlations between the maximal profiles of velocity changes *Vxr*, acceleration *Ax* and *Az* and angular velocity of the pelvic girdle inclination *Gy* can result from the fact that these values determine the dynamics of performing individual cycle phases. The values of peak-to-peak changes in the velocity of the pelvic girdle movement are higher for greater forces developed by the swimmer in the propulsive phase of the cycle and more disturbed coordination of the upper and lower limbs. High values of peak-to-peak changes in velocity cause greater energy expenditure during swimming, especially using the butterfly stroke [1]. Proper dynamics of performing individual cycle phases and good coordination of the upper and lower limbs allows for the achievement of a smooth movements that are conducive to greater mean value of translational motion velocity and lower values of fluctuation of velocity and accelerations. Low values of these parameters improve movement economy [1]. However, movement economy is less critical in races over short distances.

The statistically significant differences in basic numerical parameters of individual profiles of athletes demonstrated that the analysed profiles represent a good tool for quantitative and qualitative evaluation of movement technique in butterfly swimming.

5. Conclusion

The profile developed in the study allows for a qualitative and quantitative analysis of synchronization of movements and effective results of propulsive activity of swimmer's limbs in consecutive parts of butterfly swimming.

The analyses and comparison of the results obtained in the study with the data available in the literature reveal that the suggested method of measurement, presentation and analysis of the AG3DC profile of pelvic girdle motion may become a good tool for general evaluation of movement technique and quick and effective qualitative and quantitative biomechanical assessment of selected components of movement technique in butterfly swimming.

Acknowledgements

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