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High-frequency video capture and a computer program with frame-by-frame angle determination functionality as tools that support judging in artistic gymnastics

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Purpose: The main aim of this study was to verify the usefulness of selected simple methods of recording and fast biomechanical analysis performed by judges of artistic gymnastics in assessing a gymnast's movement technique. Material and methods: The study participants comprised six artistic gymnastics judges, who assessed back handsprings using two methods: a real-time observation method and a frame-by-frame video analysis method. They also determined flexion angles of knee and hip joints using the computer program. Results: In the case of the real-time observation method, the judges gave a total of 5.8 error points with an arithmetic mean of 0.16 points for the flexion of the knee joints. In the high-speed video analysis method, the total amounted to 8.6 error points and the mean value amounted to 0.24 error points. For the excessive flexion of hip joints, the sum of the error values was 2.2 error points and the arithmetic mean was 0.06 error points during real-time observation. The sum obtained using frame-by-frame analysis method equaled 10.8 and the mean equaled 0.30 error points. Conclusions: Error values obtained through the frame-by-frame video analysis of movement technique were higher than those obtained through the real-time observation method. The judges were able to indicate the number of the frame in which the maximal joint flexion occurred with good accuracy. Using the real-time observation method as well as the high-speed video analysis performed without determining the exact angle for assessing movement technique were found to be insufficient tools for improving the quality of judging.

Key words: *artistic gymnastics, judging, biomechanics, back handspring*

1. Introduction

A jury's assessment of technique in artistic gymnastics has on numerous occasions been the subject of criticism, controversy, and discussion on the part of judges, trainers, artistic gymnasts, as well as sports fans and commentators. Various actions have been undertaken for many years that aimed to improve the system of judging and thus limit negative factors that decrease the accuracy of the awarded scores. These actions have resulted in modifications to judging regulations developed by experts, that is, judges of the FIG (International Gymnastics Federation). In 2001, regulations were introduced that split the jury into Panel D and E [7]. Under the new system, the task of judges in Panel E is to indicate errors in observed exercises and give them adequate point values (objectively and without consulting other judges). Further modifications followed in 2006 that enable judges to award a final score of more than 10.00 points due to the 10-point value no longer constituting the maximum score achievable by gymnasts [8].

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Many researchers have attempted to investigate the reliability and objectiveness of judging. Ansorge and Scheer [2] as well as Ste-Marie [20] noted that judges awarded higher scores to athletes from their own country. Leskošek et al. [13] observed that the same phenomenon took place during the European Championship in 2011 and was slightly stronger in the finals than in the preliminaries. Boen et al. [4] discovered that knowing the point values awarded by other members of the jury significantly affected a judge's decisions. In addition, negative factors were shown to include the observation angle that resulted from where a given judge was seated, which could result in a distorted view [16]. Previous motor experience of the judges also played a considerable role, as did their specialist knowledge, recall of the observed movements, and many other factors [11], [17], [21]–[23]. Bučar-Pajek et al. [5] also reported interesting findings. During their experiment, error values given by each judge to an athlete were visible on a screen during the performed exercise. The authors indicated that such a scoring method could improve the quality of judging because points awarded to gymnasts by individual judges were explicit.

Each of the aforementioned factors may have had an immensely significant influence on the assessment of a gymnast's movement technique and thus on the final ranking in a competition. Setting aside the negative intervention on the part of judges into the awarded score, it may be assumed that most assessment errors to date have stemmed from flawed observations conducted by judges during competitions. For instance, these errors may have included a wrong assessment of flexion angles in joints [6].

One may attempt to improve the quality of judging through the methods of recording and analyzing used in biomechanics by introducing verifiable elements, thus increasing the objectivity of the assessment. Three such methods seem most easily available for practical application during gymnastic competitions: recording video of the exercises at an increased capture rate, frame-by-frame analysis of the captured video, and determining angles between selected body segments in individual frames.

The main aim of this study was to verify the usefulness of selected simple methods of recording and fast biomechanical analysis performed by judges of artistic gymnastics in assessing a gymnast's movement technique. An additional aim of the study was to determine the reliability of judging by validating the quality of both assessments performed by the judges (the traditional method and the video analysis method).

2. Material and methods

The study participants included six judges of artistic gymnastics licensed by the Polish Gymnastic Association. Each judge was also a trainer of the discipline. The number of participating judges corresponded to the number of judges in Panel E, as stipulated by judging regulations for artistic gymnastics that were in force during the experiment, that is, in 2012 [9].

The judges were asked to assess the technique of back handsprings (together with the jump and landing) performed six times by an artistic gymnast who at the time of the experiment belonged to the champion class. Categories and point values of errors used to assess the gymnast's movement technique were in accordance with judging regulations for artistic gymnastics and amounted to the following: small error = 0.1 error points, medium error = 0.3 error points, and large error = 0.5 error points. An error-free execution was recorded as 0 error points in the protocol [9].

Each performed handspring was recorded on video at a capture rate of 120 Hz (frames per second) using a Casio Exilim EX-FH25 digital camera placed on a tripod in a plane perpendicular to the direction of the gymnast's movement (in sagittal plane). Prior to recording, the gymnast had markers (specific points) placed on the left side of his body with a white, elastic adhesive tape. The markers were subsequently used to model the body in a computer program during biomechanical analysis. A majority of the markers indicated the location of the axis of rotation in selected joints in the arms (the shoulder, elbow, and wrist joints) and legs (the hip, knee, and ankle joints). The judges then used the obtained video footage to conduct a frame-by-frame assessment of the gymnast's movement technique and determine angles in selected joints. Subsequently, the authors of this study validated the angles determined by the judges based on biomechanical analysis.

The research procedure involved the following stages:

1. The judges assessed six back handsprings performed by a gymnast using the traditional (real-time observation) method. The judges were positioned in respect to the gymnast in accordance with judging regulations [9]. The judges used a protocol prepared beforehand to write a short description of each observed error by giving it an adequate error point value and indicating the precise phase of movement during which the error took place.

2. The judges conducted an assessment based on a frame-by-frame analysis of video footage. With the help of a computer and the V1 Home v.2.0 computer program, they viewed the footage frame by frame and noted the observed errors, appropriate error point values, and the number of the frame that exactly corresponded (in their opinion) to the observed error in the protocol. Before making the final decision, the judges were able to view the footage frame by frame to an accuracy of 1/120 s (recording frequency: 120 frames per second) and freely re-watch the recorded back handsprings on a computer screen.
3. The judges determined angles in the knee and hip joints using the V1 Home v.2.0 computer program. The angles were determined in those frames of the footage (selected in Stage 2) that in the judges' opinion showed the most severe error due to maximal flexion of a given joint (Fig. 1).

Fig. 1. Determining the angle with the V1 Home computer program

4. The authors of this article validated all data obtained from both assessments performed by the judges, frame numbers and angles determined by the judges for each joint and point values of ascribed errors, together with the resulting scores based on the judging regulations in force [9]. For the purposes of biomechanical analysis, a flat body model was used. It was composed of eight segments, available via the SkillSpector v.1.3.0 computer program. Symmetry of motion of the arms and legs was assumed. After indicating the location of the markers (10 points on the gymnast's body) in individual frames, selected kinematic parameters of rotational movement of the gymnast's body segments were calculated. Next, based on the plots of angular positions in knee and hip joints, obtained through the SkillSpector program, the authors validated the judges' assessment (for each of the three preceding stages). The point values of errors given by the judges during the first and second stages of the experiment were compared. The angles determined by the judges (during the third stage) with angles obtained through biomechanical analysis were also compared.

The results, that is, error values ascribed by the judges and values that characterized differences between the judges' assessments and findings of the biomechanical analysis, were analyzed using basic parameters of descriptive statistics, such as: sum of errors (Σ) (the sum of point values of errors ascribed by all the judges), arithmetic mean ($\bar{x}$) (calculated based on the combined values given by all six judges), standard deviation (SD), the minimum value (Min), the maximum value (Max), and range (R).

3. Results

Results of the judges' real-time observation (first stage of the experiment) and frame-by-frame analysis of video footage (second stage) showed that all judges noticed the flexion of knee joints error that occurred during the first flight phase (Table 1). Some judges also noticed a second technical error during the second flight phase, which they termed *excessive flexion of hip joints.* Point values given by the judges for these two errors differed between the first stage (real-time observation) and the second stage (video analysis).

During real-time observation, the judges classified the flexion of knee joints error as either small (0.1 error points) or medium (0.3 error points). During the second stage (video analysis), some judges classified the error as large (0.5 error points). The sum of point values of errors and the arithmetic means were higher in the method of frame-by-frame analysis of movement. The difference in the sum of error point values between the two assessment methods was 2.8 error points, and the difference in arithmetic means was 0.08 error points.

Considerably greater differences in error values between the two assessment methods occurred for the second observed error (excessive flexion of hip joints) than for the flexion of knee joints error. Sums of point values during frame-by-frame analysis of movement were higher than during real-time observation, but the difference between them was much higher than in the case of the flexion of knee joints error and amounted to 8.6 error points. Similarly, the difference in arithmetic means between the two assessment methods for the second observed error was much greater and amounted to 0.24 error points.

It is worth underlining that in the case of the real-time observation method, both the sum of point values of errors and the arithmetic mean were higher for the first indicated error (flexion of knee joints). This tendency was completely reversed during the frame-by-frame video analysis method, wherein the sum of the point values of errors and the arithmetic mean were higher for the second indicated error (excessive flexion of the hip joints).

Table 2 shows results pertaining to differences between the moment in which a given joint (knee or hip) was maximally flexed, as indicated by the judges in the footage, and the actual moment in which the joint was maximally flexed, as determined based on biomechanical analysis. The differences are given in absolute values (i.e., frame numbers) and as the corresponding time in the footage.

For the flexion of knee joints error, frame numbers indicated by the judges differed statistically by an average of 3.3 frames from the frame number in which maximal flexion actually occurred. The corresponding time difference equaled 0.028 s. For the excessive flexion of hip joints error, the difference in

Table 1. Results of judges' analysis of back handsprings using the real-time observation and video analysis methods

Statistical parameter	Flexion of knee joints (first flight phase)		Excessive flexion of hip joints (second flight phase)	
	Error values given during real-time observation [error points]	Error values given during video analysis [error points]	Error values given during real-time observation [error points]	Error values given during video analysis [error points]
Σ	5.8	8.6	2.2	10.8
$\bar{x}$ ± SD	0.16 ± 0.09	0.24 ± 0.13	0.06 ± 0.14	0.30 ± 0.20
Min	0.1	0.1	0.0	0.0
Max	0.3	0.5	0.5	0.5

Table 2. Differences between frame numbers indicated by the judges in the V1 Home computer program and frame numbers obtained through biomechanical analysis together with the corresponding differences in time

Statistical parameter	Flexion of knee joints (first flight phase)		Excessive flexion of hip joints (second flight phase)	
	Difference in indicated frame numbers* [frames]	Time difference [s]	Difference in indicated frame numbers [frames]	Time difference [s]
$\bar{x}$ ± SD	3.3 ± 2.6	0.028 ± 0.022	5.1 ± 3.8	0.042 ± 0.032
Min	0	0	1	0.008
Max	10	0.083	13	0.108

* Absolute values.

frame numbers between the judges' assessment and the results of biomechanical analysis was 5.1 frames, which corresponded to 0.042 s in time.

Figure 2 shows example plots (right-hand side) of angular positions in knee joints (red) and in hip joints (green), and changes of the position of the center of mass in the horizontal direction (blue), together with a frame-by-frame view of the video footage (left-hand side) during the second back handspring performed by the gymnast, obtained through biomechanical analysis.

Table 3 shows a comparison between the two observed errors: flexion of knee joints and excessive flexion of hip joints, determined by the judges and angles obtained through biomechanical analysis.

The angle at which knee joints were flexed (relative to non-flexed knees) during the first flight phase changed throughout all six back handsprings from 56° (the fifth back handspring) to 59° (the first and fourth back handsprings). For each exercise performed by the gymnast, angles determined by the judges were lower than those obtained through biomechanical analysis. The lowest difference between the results of biomechanical analysis and the angles determined by the judges was observed in the sixth handspring (1°), while the highest difference was observed in the second handspring (8°).

The angle at which the gymnast's hip joints were flexed (relative to an unbent torso) during the second flight phase obtained through biomechanical analysis

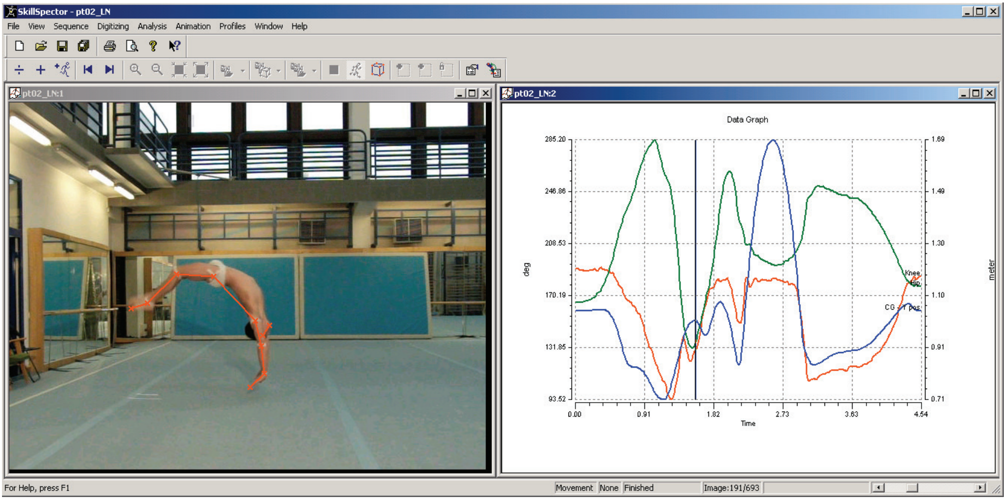

Fig. 2. Window of the SkillSpector program used to conduct biomechanical analysis

Table 3. Angles determined by the judges using the V1 Home computer program and angles obtained through biomechanical analysis for the flexion of knee joints and the excessive flexion of hip joints errors

Error	Statistical parameter*	Back Handspring 1		Back Handspring 2		Back Handspring 3		Back Handspring 4		Back Handspring 5		Back Handspring 6	
		Angle determined by judges [°]	Angle obtained by biom. an. [°]	Angle determined by judges [°]	Angle obtained by biom. an. [°]	Angle determined by judges [°]	Angle obtained by biom. an. [°]	Angle determined by judges [°]	Angle obtained by biom. an. [°]	Angle determined by judges [°]	Angle obtained by biom. an. [°]	Angle determined by judges [°]	Angle obtained by biom. an. [°]
Flexion of knee joints	$\bar{x}$	55	59	50	58	54	57	57	59	53	56	56	57
	SD	1		5		3		3		2		3	
	Min	53		41		50		53		50		53	
	Max	56		53		59		61		54		59	
	R	3		12		9		8		4		6	
	Difference**	4		8		3		2		3		1	
Excessive flexion of hip joints	$\bar{x}$	78	82	76	83	73	80	75	82	80	85	76	81
	SD	5		5		9		7		8		4	
	Min	70		69		62		67		66		71	
	Max	83		81		80		81		86		79	
	R	13		12		18		14		20		8	
	Difference**	4		7		7		7		5		5	

* Concerns values determined by the judges during video analysis.
** Difference between the angle obtained through biomechanical analysis and the angle determined by the judges (absolute value).

ranges from 80° (the third handspring) to 85° (the fifth handspring) throughout all six back handsprings. Similarly to the flexion of knee joints error, the angles determined by the judges were lower in all back handsprings performed by the gymnast than those obtained through biomechanical analysis. The lowest difference between the results of biomechanical analysis and the judges' assessment was 4° (the first handspring) and the highest amounted to 7° (the second, third, and fourth handspring).

Table 4 shows error point values given by the judges for the flexion of knee joints error during real-time observation and video analysis compared to the actual values obtained through biomechanical analysis and based on the regulations in force [9].

Table 4. Point values given by the judges for the flexion of knee joints error during real-time observation and video analysis and actual values obtained through biomechanical analysis and based on the regulations for each back handspring

Statistical parameter	Back Handspring 1			Back Handspring 2			Back Handspring 3			Back Handspring 4			Back Handspring 5			Back Handspring 6		
	Live observation [points]	Video analysis [points]	Actual value [points]	Live observation [points]	Video analysis [points]	Actual value [points]	Live observation [points]	Video analysis points]	Actual value [points]	Live observation [points]	Video analysis [points]	Actual value [points]	Live observation [points]	Video analysis [points]	Actual value [points]	Live observation [points]	Video analysis [points]	Actual value [points]
$\bar{x}$	0.17	0.27		0.17	0.17		0.17	0.23		0.17	0.27		0.17	0.23		0.13	0.27	
SD	0.10	0.15		0.10	0.10		0.10	0.10		0.10	0.15		0.10	0.16		0.08	0.15	
Min	0.10	0.10	0.50	0.10	0.10	0.50	0.10	0.10	0.50	0.10	0.10	0.50	0.10	0.10	0.50	0.10	0.10	0.50
Max	0.30	0.50		0.30	0.30		0.30	0.30		0.30	0.50		0.30	0.50		0.30	0.50	
R	0.20	0.40		0.20	0.20		0.20	0.20		0.20	0.40		0.20	0.40		0.20	0.40	

It is worth noting that no arithmetic mean assessed through real-time observation and video analysis corresponded to the actual value of the error and all arithmetic means were lower than the actual value. Minimum values during real-time observation belonged to the small error category (0.1 points), while maximum values belonged to the medium error category (0.3 points). Conversely, minimum values during video analysis belonged to the small error category (0.1 points), while maximum values given by some judges belonged to the large error category (0.5 points, given for the first, fourth, fifth, and sixth back handspring). Thus, arithmetic means reached values that were closer to the actual value of the error.

Because the regulations in force [9] do not precisely stipulate an acceptable flexion in the hip joints during the second flight phase, the authors of this article did not conduct a similar comparison in respect to the second error (excessive flexion of the hip joints).

4. Discussion

Attempts at eliminating negative factors that decrease the quality of judging in artistic gymnastics will, with all probability, be the subject of numerous discussions and analyses on the part of researchers and experts in artistic gymnastics. However, it seems that some factors can be eliminated by applying modern video and computer technologies in the system of judging. For this reason, the authors of this study attempted to investigate whether using frame-by-frame video analysis and a computer program with angle determination functionality can constitute effective support tools for judges. The primary research subject of this study was only possible to verify by using a detailed biomechanical analysis, which was conducted through the SkillSpector computer program.

The authors chose to conduct this study based on the back handspring, as it is an important component in technical preparation of artistic gymnasts [3], [19]. Judging regulations classify this exercise under Group A in terms of difficulty. In terms of structure, the regulations consider the back handspring a backwards acrobatic element [9]. Thus, it may be assumed that the judges who participated in this study had assessed this exercise on numerous occasions during gymnastic competitions.

All judges observed the flexion of knee joints error when assessing the back handsprings through the real-time observation method. The error occurred during a phase referred to as the first flight phase. The start point of this phase was assumed to be the instant the gymnast's feet left the ground after springing from his legs and the end point to be the moment the gymnast's hands touched the ground [1], [10]. According to Penitente et al. [15], the first flight phase constitutes a component of the back handspring that lasts for about 0.27 s (arithmetic mean obtained by female gymnasts at various level of skill). Such a short duration of a significant phase of the exercise imposes demanding requirements on the judges in terms of noticing errors and ascribing appropriate point values to them. It has even been proved that in static exercises performed with rings, which allow for a longer observation of the gymnast's assumed position, judges evaluate technical errors differently [6], [17].

While all judges in this study agreed on what errors occurred (in each back handspring) during the real-time observation method, they gave them different error point values: either 0.1 error points (small error) or 0.3 error points (medium error). It may be assumed with a good degree of probability that these differences were due to flaws in the judges' observations. Surprisingly, video analysis of movement only increased the differences in assessments of the error. Some judges interpreted the observed flexion of knee joints as a large error (0.5 error points) during the frame-by-frame analysis. This tendency is completely opposite to that shown in a study by Puhl [18], who noticed greater differences in assessments in the real-time observation method than in the video analysis method.

In the second stage of the procedure used in this research, some judges correctly assessed the flexion of knee joints error as large during video analysis (which required them to change their previous decisions). Four back handsprings received maximal error values (0.5 points). The remaining two handsprings received 0.3 points (medium error). The applied biomechanical analysis as well as angles determined by the judges (using the V1 Home v.2.0 program) showed that the flexion exceeded the angle of 45° in each handspring performed by the gymnast. According to judging regulations that were in force during the time of the experiment, the appropriate value for such an error should have amounted to 0.5 points [9]. The results presented above allowed us to formulate the conclusion that using frame-by-frame video analysis to assess gymnastic exercises did not allow for an unambiguous and accurate (i.e., in accordance with the actual state) assessment of error on the part of all the judges. It should be emphasized that in the real-time observation method, no judge ascribed the proper value to the flexion of knee joints error.

Some judges indicated another error, that is, excessive flexion of hip joints, during the second flight phase. In this case, the differences between the judges' assessment were prominent in both methods of movement analysis. Some judges did not consider the flexion to be incorrect, while other judges recorded it as a large error (0.5 points). These differences were likely due to the judges' varying approaches to assessing movement technique, in this case, the acceptable or even required flexion of the hip joints during the second flight phase. A lack of unambiguously described correct technique of gymnastic exercises likely constitutes another factor that decreases the objectivity of judging [11], [23]. Practitioners and theoreticians who analyze the technique of gymnastic exercises indicated that after jumping from the hands, a gymnast should swing their legs downwards through a forward bend of the torso [12]. However, literature lacks precise data on the optimal range of flexion in the hip joints during the second flight stage of the back handspring. Assessing the optimal range should, therefore, be the subject of detailed biomechanical analyses that could allow researchers to develop a clear and concise description of the movement technique. Developing such a description would improve the quality of judging and, perhaps, the process of gymnast training as well. In this study, maximal flexion of hip joints during the second flight stage ranged from 80° to 85°. Such a high flexion was likely due to an incorrect jump from the hands, which in turn resulted in a low second flight stage and, as a consequence, in a high flexion of the hip joints. Therefore, the phenomenon of a negative transfer of error between the subsequent phases of movement may have been involved here; the phenomenon has often led to an incorrect landing position or even a fall [14], [24]. Considerably higher error values ascribed by the judges based on video analysis indicate that, following the analysis some judges decided that the observed flexion in this phase of movement was too high. Nevertheless, the judges assessed the error to be on average only a medium error (0.3 points).

Biomechanical analyses are a perfect tool for assessing the technique of movements performed by artistic gymnasts. However, such analyses require researchers to use procedures that are time-consuming and thus prevent effective application in gymnastic competitions. One of the crucial and at the same time most difficult tasks of a judge is to determine the angles between body segments and the position of the body relative to the exercise apparatus. The angles and the position form the basis on which observed errors are given the appropriate point values [9]. Actual error values should correspond to the maximal range of flexion in given joints. This is why using a computer program with an angle determination functionality (V1 Home v.2.0) requires finding the frame of the footage in which the maximal flexion occurred in advance.

A comparison between frame numbers indicated by the judges and the results of biomechanical analysis allowed for the conclusion that the judges were able to accurately indicate the frame in which the maximal flexion occurred or frames in the vicinity to that frame. Differences in frame numbers between the two methods of analysis amounted to $\bar{x}$ 3.3 frames for the flexion of knee joints error during the first flight stage and $\bar{x}$ 5.1 frames for the excessive flexion of hip joints error during the second flight stage. One may assume that at a capture rate of 120 Hz, these differences were small, and therefore insignificant.

In some cases (minimum values of differences between frame numbers of 0; *viz*. Table 2), the judges indicated the exact frame in which the maximal flexion in the joints occurred. Therefore, it may be stated that the judges indicated that particular moment in a satisfactory manner, thus enabling them to determine the angle more accurately.

The angle of flexion in the knee joint that the judges determined through the computer program differed slightly from the angle obtained by means of biomechanical analysis. On average, the difference amounted to 4°. In the case of the excessive flexion of hip joints error, it may be assumed that the considerable difference in frame numbers between the judges' assessment and the results of biomechanical analysis also contributed to greater differences between angles obtained through both types of analysis. The differences between angles on average amounted to 6.2°.

The aforementioned case of the flexion of knee joints error during the first flight stage allowed for the conclusion that the judges of artistic gymnastics were able to notice errors in dynamic movements during real-time assessment. Moreover, they were able to accurately indicate the moment in which maximal flexion of the joint occurred during frame-by-frame video analysis. Results related to the second error observed by the judges also confirmed this ability. It seems, therefore, that the main factor that contributed to a decrease in the level of judging objectivity was the difficulty to properly categorize an error and, consequently, to give it an appropriate point value. While differences between judges' assessment and actual error values were understandable in case of real-time observation, the authors were surprised to find that such differences still occurred after using the video analysis method. A comparison of research results showed that applying a frame-by-frame analysis of movement did not benefit the assessment of technique, since the judges still determined the angles between selected body segments wrongly. Results of the judges' assessment of angles by means of the third assessment method showed that applying a user-friendly computer program gave an opportunity for increasing the quality of judging by determining angles that are close to the actual angles.

The study also found that the judges interpreted the flexion of hip joints during the second flight stage differently. Some of them observed no technical faults, while others concluded that the scope of flexion corresponds to a large error. Another surprising finding was that the differences between judges' assessments were greater for the video analysis method than for the real-time observation method. In this case, even an accurate determination of angles in hip joints did not allow the authors to decide which ascribed error values were accurate and which were not due to the fact that judging regulations do not precisely indicate what range of hip flexion in this exercise can be considered correct [9]. This suggests that the correct technique of the back handspring, as well as other gymnastic exercises, needs to be described in more detail. A more detailed description could significantly contribute to an increase in the quality of judging in artistic gymnastics.

The authors of this study are aware that applying an efficient, user-friendly computer program with angle determination functionality will not solve every judging difficulty. However, it is worth attempting to gradually implement such a system in competitions. It seems that a computer program similar to the one described here could, without any reservations, be used today by the referees and judges of individual disciplines and applied whenever members of the jury differ considerably in their awarded scores. Without a doubt, such a program could constitute a perfect tool for resolving protests filed by trainers during competitions.

It is worth emphasizing that the computer methods of movement assessment presented in this study may find a broader application. These methods allow trainers to obtain detailed information on the level of trainees' gymnastic skills as well as the changes that occur in the movement technique during the long-term process of the technical preparation of gymnasts.

5. Conclusions

1. The judges indicated the same errors in back handsprings performed by a gymnast during both real-time observation and video analysis. However, the judges ascribed different point values to these errors (values based on the frame-by-frame video analysis of movement were higher than those based on real-time observation).
2. A validation of the point values ascribed by the judges showed that using only a frame-by-frame analysis without the possibility of determining the angle was insufficient as tool for improving the

quality of judging, as the judges still assessed the angles wrongly.

3. Analysis of study results allowed the authors to conclude that the judges were able to indicate with good accuracy the number of the frame in which a flexion of a joint occurred that corresponded to the maximal error value. For this reason, using a computer program to assess the technique of movement based on obtained angles seems possible and advisable.
4. All three elements taken from biomechanics and validated in this study, that is, recording video footage, frame-by-frame analysis of movement, and using a computer program to determine angles, were found to be effective and user-friendly tools for improving the quality and objectivity of judging.

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