Acta Gymnica, vol. 45, no. 1, 2015, 33–40
doi: 10.5507/ag.2015.005

The "Akopian" vault performed by elite male gymnasts: Which biomechanical variables are related to a judge's score?

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Background: A vaulting performance takes a short time and it is influenced by and affects the quantity of mechanical variables. The significant relationships between the vaulting score and specific aspects of the gymnast's vault should conduct coaches to monitor these variables as a part of training or routine testing. **Objective:** The aim of the current study was to determine the biomechanical variables that are related to a successful performance of the Akopian vaults performed by top level male gymnasts during the World Cup competition. **Methods:** Fifteen top-level male gymnasts participated in this study. For the 3D analysis, two digital camcorders with a frame rate of 50 Hz were used. The data were digitized by the Simi motion software. The Hay and Reid method was used to identify the biomechanical variables that determine the linear and angular motions of the handspring and front somersault vaults. A correlation analysis was used to establish the relationship between the biomechanical variables and the judges' scores. The level of statistical significance was determined at the value of $p < .05$. **Results:** In the Akopian vaults, in five out of 24 variables arising from the deterministic model showed a significant relationship to the score. A significant correlation was found in the maximum height of the body center of mass in the second flight phase, in the height of the body center of mass at the mat touchdown, in the change of the vertical velocity during the take-off from the vaulting table, and in the duration of the second flight phase. **Conclusions:** The results of the study suggest that a successful execution of Akopian vaults and the achievement of a higher score required: to maximize the change in vertical velocity in the table contact phase and maximize vertical velocity in the table take-off phase; to maximize the amplitude of the second flight phase, which is determined by the duration of the second flight phase, by the maximum height of the body center of mass in the second flight phase and by the distance of the vaulting table during landing; and to maximize the height of the body center of mass in the mat contact phase.

Keywords: sports biomechanics, kinematics analysis, technique, correlation analysis, judge's score

Introduction

At the World Championship in Ljubljana 1970, a gymnast performed an extra somersault in the second flight phase for the first time. The new vault was performed by Japanese gymnast Mitsuo Tsukahara, who had a great influence on the development of the today's vault. The cartwheel with a 90° turn and a somersault backward is named after Tsukahara and many of the contemporary vaults carry his name (Cuk & Karacsony, 2004). Tsukahara is the continuous rotation vault, in which the rotation of the body along the gymnast's transverse (or somersault) axis is in the same forward direction throughout (Takei, Blucker, Nohara, & Yamashita, 2000). In gymnastics judging, the evaluation of routines in their execution is based on the form and techniques displayed during the performance (Takei, 1992). The primary determinant of success is the ability to perform a high difficulty exercise with a high execution score (Massidda & Caló, 2011). Artistic gymnastics is evaluated live by a panel of accredited judges using governing rules and performance-based criteria known as the Code of Points (Federation International de Gymnastique, 2013) to guide their observations (Bradshaw, Hume, & Aisbett, 2012).

Vaulting is the only gymnastic apparatus involving a single movement and, for this reason, vaulting is the most researched and best understood apparatus (Prassas, Kwon, & Sands, 2006). A vaulting performance

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takes a short time and it is influenced by and affects the quantity of mechanical variables (Farana & Vaverka, 2012). Some of the previous studies discuss the issue of biomechanical factors in the individual vault phases and their effect on the achieved score using deterministic models (Takei, Dunn, & Blucker, 2003; Takei et al., 2000). A deterministic model is a paradigm that determines the relationship between a movement outcome measure and the biomechanical factors that produce such a measure (Chow & Knudson, 2011). The aim of the theoretical models in artistic gymnastics is to indicate the relationship between the resulting score and variables that affect the final score (Farana & Vaverka, 2012; Krug, Knoll, Köthe, & Zocher, 1998; Naundorf, Brehmer, Knoll, Bronst, & Wagner, 2008; Penitente, Merni, & Fantozzi, 2009; Prassas, 2002; Takei, 1990, 1992, 1998, 2007; Takei et al., 2000; Van der Eb et al., 2012) or to optimize the course of the movement in the vault (Gervais, 1994). Evaluating changes in these predictive variables could highlight the gymnast's training progress between competitions (Bradshaw, Hume, Calton, & Aisbett, 2010). Previous studies deal with the relationship between the final score and the biomechanical factors of somersault vaults (Farana & Vaverka, 2012; Takei, 1990, 1992, 1998, 2007), Yurchenko vaults (Penitente et al., 2009) and Hecht vaults (Takei et al., 2000). Other studies focus on the actual relationship between the running approach velocity and the resulting score (Krug et al., 1998; Naundorf et al., 2008; Veličković, Petković, & Petković, 2011; Van der Eb et al., 2012). Cuk and Forbes (2010) highlighted that the vault D-scores significantly differ from other apparatus and on the vault there was not enough discrimination among gymnast's D-scores. Previous studies by Atikovic and Smaljovic (2011) and Atikovic (2012) defined that degrees of turnaround transversal axis and degrees of turns around longitudinal axis in the second flight phase were predictors of the vault difficulty value. Even though the Tsukahara vault is common in competitive gymnastics (Farana, Uchytil, Jandačka, Zahradník, & Vaverka, 2014), there is a paucity of research examining the relationship between the biomechanical factors and the resulting score in this group of vaults in male gymnastics. Thus, the current study focuses on a performance of the Tsukahara vaults (FIG, 2013), executed by the elite male artistic gymnasts who participated in the World Cup competition.

The aim of the current study was to determine the mechanical variables that are related to a successful performance of the "Akopian" vaults performed by top level male gymnasts during the World Cup competition. The significant relationships between the vaulting score and specific aspects of the gymnast's vault could compel coaches to monitor these variables as a part of training or routine testing. Information obtained from the current study could make vault training program more effective, efficient and safer.

Methods

Participants

Fifteen top-level male gymnasts who participated in the 2010 and 2011 World Cup competitions in the Czech Republic were involved in this study. All gymnasts were members of the national teams of the relevant countries. Both competitions took place in the competition period approximately two weeks before the World Championships in Tokyo in 2010 and London in 2011, respectively. The age, height and mass of gymnasts were 21.40 ± 1.88 years, 167.80 ± 4.71 cm and 64.60 ± 4.50 kg, respectively. All gymnasts performed the Tsukahara vault (straight Tsukahara with a 2/1 twist – Akopian) graded 6.2 points (FIG, 2009). The final score for vaults were 14.90 ± 0.50 points.

Data collection

For the 3D spatial movement analysis, two digital camcorders (Panasonic NV-MX500EG, Panasonic, Kadoma, Japan) with a frame rate of 50 Hz were used. The shutter speed was set to 1/500 s. The angle between the optical axes of the cameras was near to 90° (Bartlett, 2007). The calibration pole was defined with a calibration bar and was defined by a virtual cuboid of 7 × 4 × 3 m (Figure 1).

Data analysis

The data was digitized by the SIMI MOTION software (SIMI Reality Motion Systems, Unterschleissheim, Germany). In each frame, the gymnast's head center and his hand, wrist, elbow, shoulder, hip, knee, ankle and toe on both sides of his body were digitized. A 14-segment model of the human body was created based on 17 body points. For the location of the center of mass (COM), the Gubitz model (Gubitz, 1978) was used. For each vault, approximately 75 fields were digitized. These included every frame from five frames prior to the board touchdown to five after the mat touchdown. The length of the assessed take was 1.5 seconds in all evaluated vaults. The 3D DLT method was used for calculating 3D coordinates of the digitized body parts (Abdel-Aziz & Karara, 1971). The raw data were smoothed using a low-pass filter with the cut-off frequency of 8 Hz (Bartlett, 2007). The reconstruction accuracy for each dimension was < 0.015 m (Kerwin & Irwin, 2010; Manning, Irwin, Gittoes, & Kerwin, 2011). A sample vault trial was digitized twice to evaluate digitizer reliability (Irwin & Kerwin, 2009;

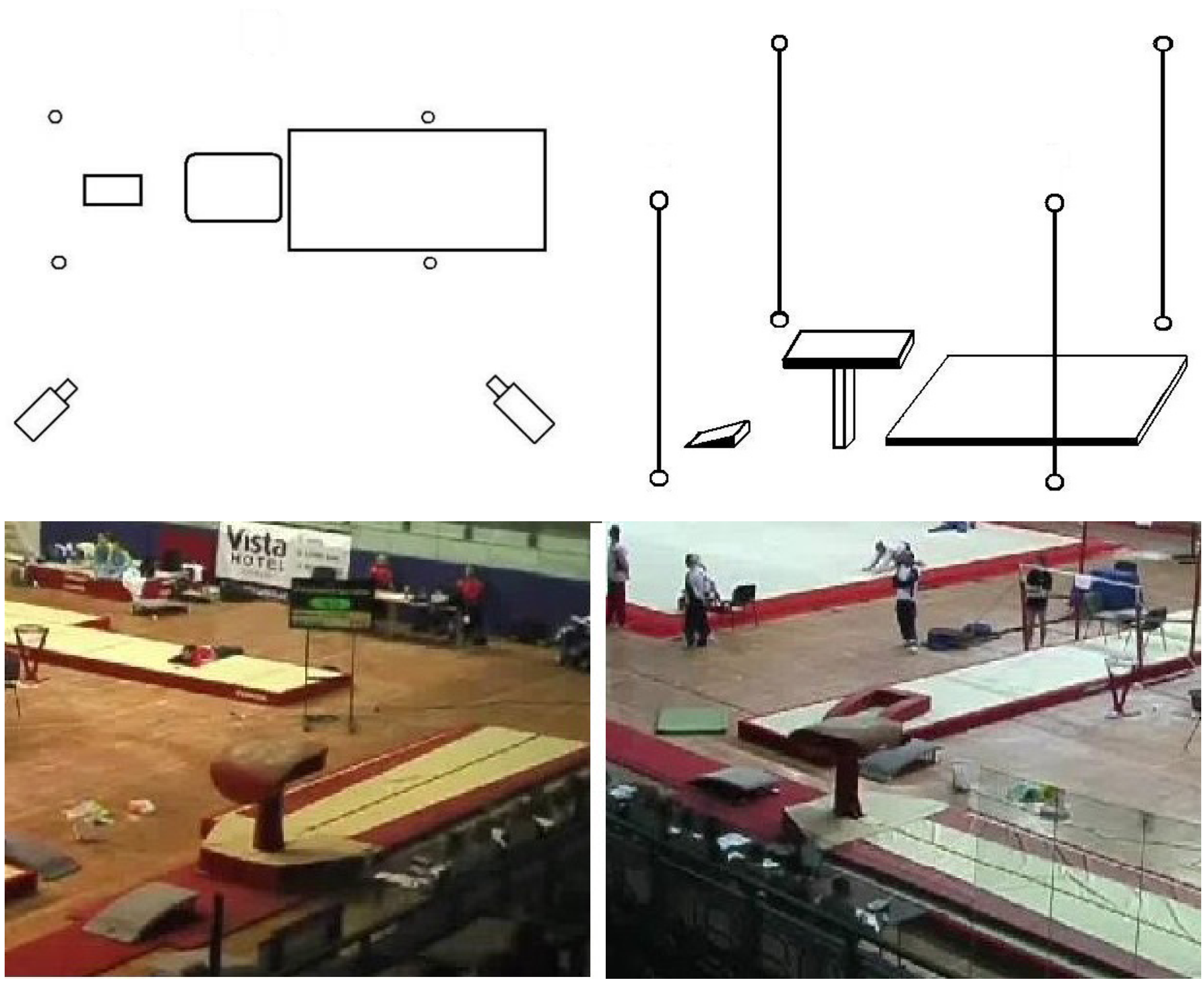

Figure 1. Calibration volume, camera set-up and vaulting apparatus

Kerwin & Irwin, 2010). Reliability based on repeat digitization of a sample sequence was < 1 % for temporal and spatial parameters and < 4.5 % for velocity parameters. The data were manually digitized by an experienced researcher (Janura, Cabell, Svoboda, Elfmark, & Zahálka, 2011).

Measured biomechanical variables

A theoretical model of biomechanical variables was used, according to the method of Hay and Reid (1988) and study by Takei et al. (2000), to identify the mechanical variables that determine the linear motions of the gymnast performing handspring and front somersault vaults (Figure 2).

According to Hay and Reid (1988), the model used in our study consisted of two factors (the trajectory of COM in the first flight and the trajectory of COM in the second flight) which are identified at the second level and linked to the points awarded by judges at the first level. The trajectory of the COM in the pre-flight is governed by the resultant velocity at the take-off from the board, the relative height of the take-off and the time of the first flight (3rd level). The resultant velocity at the take-off from the board is the vector sum of the horizontal and vertical velocities at the take-off (4th level). The relative height of the take-off is determined by the height of the COM at the board take-off and the height of the COM at the table touchdown (4th level). The time of the first flight is determined by the height of the COM and the vertical velocity at the take-off from the board and the height of the COM at the touchdown on the table (4th level). The mechanical variables which govern the trajectory of the COM in the second flight phase are similar to those identified on the third and fourth levels of the model for the first flight. More specifically, the vertical velocity at the take-off from the table shown at the fourth level is the sum of the vertical velocity at the touchdown on the table and the change in the vertical velocity that occurs while on the table (5th level). The horizontal velocity at the take-off from

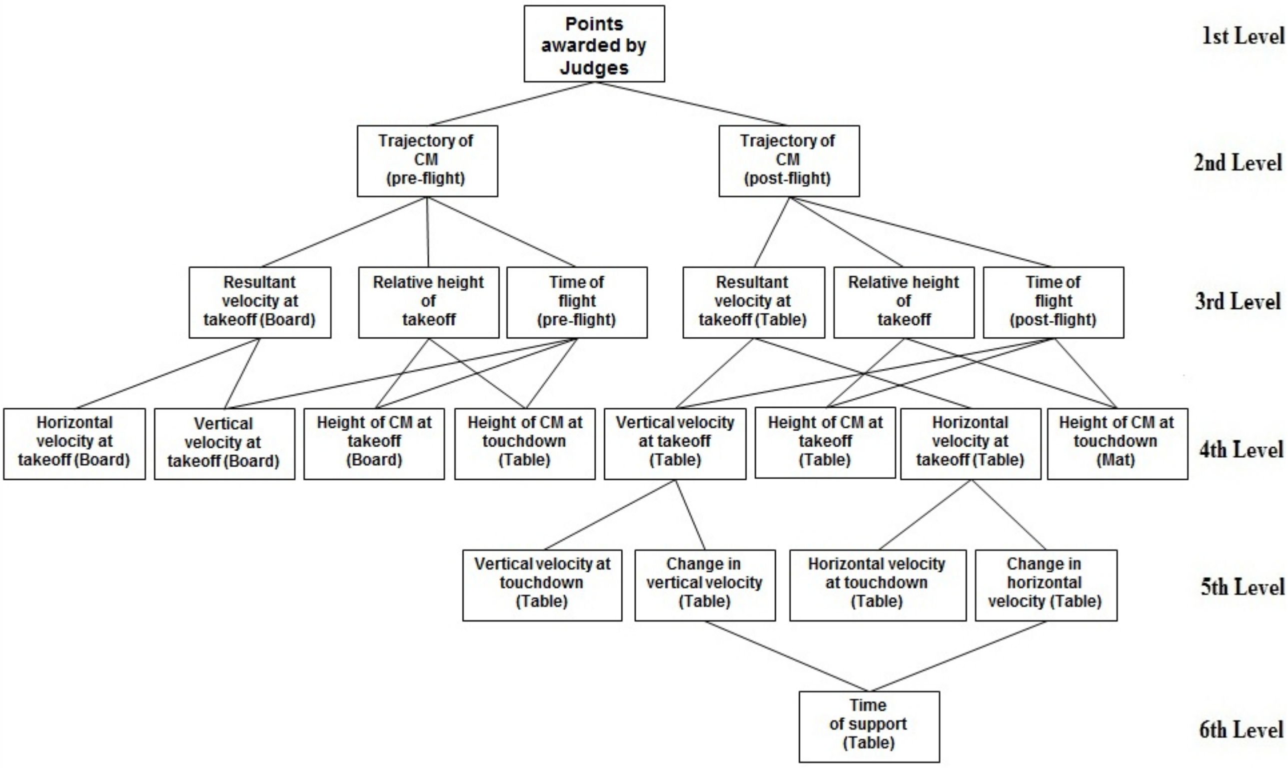

Figure 2. Model showing factors that determine the linear motions of the Tsukahara vault related to the judges' score

the table shown at the fourth level is the sum of the horizontal velocity at the touchdown on the table and the change in the horizontal velocity that occurs while on the table (5th level). The changes in the vertical and horizontal velocities are determined by the duration of the table support (6th level).

Statistical analysis

The mean and standard deviations were calculated for each variable. The box-plot was used for outlier identification. Pearson correlation (r) coefficient was used to express the statistical relation between the dependent variables and independent variables. The level of statistical significance was determined to be $p < .05$. A coefficient of determination (r^2) was calculated for all independent variables and expresses the relation of the explained variability to the total variability of dependent variable (Takei, 2007). Any variable that can explain more than 10% of the variability of judge's score considered as practically significant (Takei, 2007). IBM SPSS Statistics (version 19; IBM, Armonk, NY, USA) was used for statistical analysis.

Results

The descriptive statistics, correlation coefficients and the coefficient of determination for the time, velocity, spatial and angular parameters of the eight vaults executed by the male gymnasts from vaults Group 4 (vaults with a 1/4 turn in the pre-flight – Tsukahara and Kasamatsu) that achieved the highest score are outlined in Table 1 and 2.

Regarding the temporal and spatial parameters, a total of fifteen variables were examined, while a significant relationship to the score was found in three variables (Table 1). As for the temporal parameters, a significant correlation was found in the time of the second flight phase ($r = .67$; $p = .003$). Practically significant relationships were found in the time of the board contact ($r^2 = .12$).

As for the spatial variables, practically significant relationships were found in the official distance of the second flight ($r^2 = .18$). Significant relationships to the score were found in the maximum height of the body COM in the second flight phase ($r = .57$; $p = .013$) and the vertical height of the body COM at the mat touchdown ($r = .55$; $p = .017$). Practically significant relationships were found in the height of the body COM during the take-off from the vaulting table and the relative height of the COM at the table take-off and the height of the center of mass at the mat touchdown ($r^2 = .13$).

As for the velocity parameters, a total of nine variables were examined, while a significant relationship was determined in two of them (Table 2). A significant

Table 1
Relationship between temporal and spatial variables and the judges' score in critical phases of the vault (N = 15)

Variable	Mean ± *SD*	Minimum	Maximum	*r*	r^2
Judges score	14.90 ± 0.50	13.60	15.50	–	–
Time (s)					
On board	0.11 ± 0.02	0.08	0.12	–.35	.12
First flight	0.09 ± 0.01	0.08	0.12	.24	.06
On table	0.26 ± 0.02	0.22	0.28	–.28	.08
Second flight	0.89 ± 0.04	0.80	0.96	.67**	.45
Horizontal displacement of COM (m)					
First flight	0.55 ± 0.20	0.25	1.13	.08	.01
Second flight	3.73 ± 0.19	3.41	4.02	.26	.07
Official distance of second flight	2.58 ± 0.21	2.21	3.02	.42	.18
Height of COM at critical instants (m)					
Board take-off	1.27 ± 0.09	1.10	1.43	.09	.01
Table touchdown	1.58 ± 0.11	1.43	1.88	.08	.01
Table take-off	2.35 ± 0.07	2.21	2.48	.40	.16
Peak of second flight	2.68 ± 0.11	2.51	2.85	.57*	.32
Mat touchdown	0.92 ± 0.10	0.73	1.10	.55*	.30
Relative height of take-off (m)					
Board take-off to table touchdown	0.31 ± 0.12	0.15	0.67	.02	.01
Table touchdown to table take-off	0.78 ± 0.11	0.69	0.92	.18	.03
Table take-off to mat touchdown	1.43 ± 0.09	1.27	1.59	–.36	.13

Note. *r* = Pearson coefficient of correlation, r^2 = coefficient of determination. *$p < .05$, **$p < .01$.

Table 2
Relationship between velocity variables and the judges' score in critical phases of the vault (N = 15)

Variable	Mean ± *SD*	Minimum	Maximum	*r*	r^2
Judges score	14.90 ± 0.50	13.60	15.50	–	–
Resultant velocity (m/s)					
Board take-off	6.23 ± 0.45	5.47	6.97	.03	.01
Table take-off	4.30 ± 0.36	3.78	4.93	.31	.10
Horizontal velocity (m/s)					
Board take-off	5.07 ± 0.42	4.40	5.74	.12	.01
Change on table	–1.42 ± 0.40	–2.09	–0.91	–.27	.07
Table take-off	3.37 ± 0.33	2.85	3.94	–.15	.02
Vertical velocity (m/s)					
Board take-off	3.61 ± 0.34	2.95	4.10	–.29	.08
Table touchdown	3.41 ± 0.22	3.08	3.82	–.22	.05
Change on table	–0.79 ± 0.54	–2.25	–0.13	.56*	.31
Table take-off	2.62 ± 0.46	1.57	3.35	.55*	.30

Note. *r* = Pearson coefficient of correlation, r^2 = coefficient of determination. *$p < .05$.

relationship was found in the change in the vertical velocity of the body COM at the table take off ($r = .56$; $p = .016$) and the vertical velocity of the body COM at the table take-off ($r = .55$; $p = .017$). Practically significant relationships were found in the resultant velocity of the body COM at the table take-off ($r^2 = .10$).

Discussion

Temporal and spatial parameters and judges' score

As for the temporal parameters, a significant relationship was found ($r = -.67$; $p = .003$) in the time of the second flight phase. This variable can explain about

45% of the variability of the score. A significant relationship implies that the longer the second flight phase is, the higher the score the gymnast achieves. Takei et al. (2000) also found significant relationships to the score in these variables. On vault gymnasts are required to rotate about the longitudinal and the transverse axis in a well-defined manner (Heinen, Jeraj, Vinken, & Velentzas, 2012). Thus an increase in second flight time provides gymnasts with the ability to complete more complex acrobatic skills in the air, increasing the degree of difficulty and the potential for a high score (Bradshaw et al., 2010). The time of the board contact in the Tsukahara vaults can explain about 12% of the total variability of the score and this variable can be considered to be practically significant (Takei, 2007). It means that the shorter the duration of the take-off phase, the better the execution of the vault is and the better the possibility of a higher score is. This has also been confirmed by Bradshaw and Sparrow (2001) who characterize an explosive take-off by the short duration of the contact that is in a moderate correlation with the duration of the second flight phase ($r = -.41$; $p < .05$) and the resulting score ($r = -.59$; $p < .05$). A brief contact time on the take-off board and/or vaulting table is likely to translate the gymnast's approach velocity into a longer second flight time (Bradshaw, 2004). It seems that the temporal parameters are observable variables from the aspect of the score and thus it is possible to partially predict a successful score. As Bradshaw et al. (2010) state, temporal variables are an important and reliable training indicator of vaults from various groups at various performance levels of competitive gymnasts.

As for the spatial parameters, significant relationships were found in the maximum height of the body COM in the second flight phase ($r = .57$; $p < .05$) and the vertical height of the body COM at the mat touchdown ($r = .55$; $p < .01$). These two variables are very important for further training from the aspect of statistical significance as the achieved maximum height of the body COM can explain about 32% and the height of the body COM at the mat touchdown can explain up to 30% of the total variability of the score. The Code of Points states that somersault vaults must display a distinct opening phase in preparation for landing (FIG, 2009). To observe this rule, the time of the second flight phase and the height of the body COM at the mat touchdown are decisive. The previous studies by Takei (2007) and Takei, Dunn, and Blucker (2003) confirm the significance of those variables from the aspect of the score. Takei (2007) found a significant relationship to the score in both variables in the "Roche" vault. Takei, Dunn, and Blucker (2003) found significant differences ($p < .005$) between the "Roche" vaults that obtained higher and lower scores. The vaults with a higher score reached a higher height of the body COM during the second flight phase as well as at the mat touchdown. As Prassas (2002) states, the height of the body COM at the mat touchdown determines the level of squat and incomplete rotation during landing. It is thus clear that these two variables may be considered important from the score aspect. Surprisingly, no significant relationship between the horizontal distance of the body COM and the score was found. However, the official distance during landing may also be considered practically significant and it may explain about 18% of the score variability. Previous studies (Takei et al., 2000; Takei, 2007) found significant relationships for those variables. We explain this contradiction by the fact that the gymnasts in our study landed in a sufficient distance from the vaulting table in both examined vaults and also that the rules of competitive gymnastics do not determine a prescribed distance (FIG, 2009). From the coaching point of view, George (2010) states that a trajectory of the second flight phase that is comparatively higher and shorter allows the body to follow a more vertical path at touchdown, thereby minimizing unwarranted horizontal motion.

Velocity parameters and judge's score

As for the velocity parameters, a significant correlation was found in the vertical velocity at the table take-off ($r = .55$; $p < .05$). This variable can explain about 30% of the total score variability. Vertical velocity is considered to be the key variable in achieving a sufficient height of the vault, which is also confirmed by the results of previous studies (Cuk & Karacsony, 2004; Takei, 1998; Takei, Dunn, & Blucker, 2003; Takei & Kim, 1990; Prassas, 2002). Irwin and Kerwin (2009) found that the introduction of a new vaulting table significantly increased vertical velocity in somersault vaults in the phase of the table take-off. We can thus presume that when a gymnast takes off the vaulting table with a high vertical velocity, he will achieve a sufficient height during the second flight phase and have thus a higher potential of obtaining a higher score. According to the Code of Points, the gymnast must demonstrate a distinct rise in the height of his body after the take-off from the table and the gymnast must show a conspicuous rise of his center of gravity above its height at the moment of the hand take-off (FIG, 2009). To observe these rules, a high vertical velocity during the take-off from the vaulting table thanks to which the gymnast obtains a sufficient height of the second flight phase is necessary. Vertical velocity can be thus considered a variable that can partially predict the score. A significant relationship in the change of vertical velocity during the take-off from the vaulting table was found in the Tsukahara vaults ($r = .57$;

$p < .05$). This means that gymnasts are able to produce a high vertical velocity important for the height of the second flight phase and controlled landing in the short time interval of the vaulting table take-off phase. Takei et al. (2000) also achieved similar results in the "Hecht" vault: they state that a short time of the table support, a high vertical impulse and increase in vertical velocity during the take-off are necessary for a higher score. George (2010) states that to sticking the landing, the vertical component is always easier to control than the horizontal.

Although our study has brought some interesting findings in the field of kinematics of the examined group of vaults, to understand this issue better, it is necessary to work with a wider sample size of top-level gymnasts under the conditions of a real competition and to broaden the research to vaults from other vault groups (e.g. Yurchenko group). Moreover, due to small sample size external validity of the current research is limited. However, small sample sizes are a common feature when undertaking research at elite competition (Kerwin & Irwin, 2010; Manning et al., 2011).

Conclusions

Based on the deterministic model, we determined variables that have a significant effect on the score concerning vaults from the Tsukahara group. Therefore, we can state that the deterministic model we used showed significant relations that significantly participate in the score of the performed vaults in accordance with the rules of competitive gymnastics.

In the Tsukahara vaults, in five out of 24 variables arising from the deterministic model showed a significant relationship to the score. The results of the study imply that the following is required for a successful execution of Akopian vaults and the achievement of a higher score:

- To maximize the change in vertical velocity in the table contact phase and thus maximize vertical velocity in the table take-off phase.
- To maximize the height of the body COM in the mat contact phase.
- To maximize the amplitude of the second flight phase, which is determined by the duration of the second flight phase, by the maximum height of the body COM in the second flight phase and by the distance of the vaulting table during landing.

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