RELATION BETWEEN VAULT DIFFICULTY VALUES AND BIOMECHANICAL PARAMETERS IN MEN'S ARTISTIC GYMNASTICS

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Original research article

Abstract

The aim of the paper is to define which biomechanical parameters explain and define the difficulty vault value. The study sample included 64 vaults from the Code of Points (COP) of the International Gymnastics Federation (FIG, 2009). The dependent variable included all difficulty values ranging from 2-7.2 points, while the sample of independent variables included 12 biomechanical variables (data was collected from the literature and our measurements). With regression analysis we explained 92.4% of the difficulty vault value. Only three biomechanical variables were predictors: degrees of turns around transversal axis, degrees of turns around longitudinal axis and body's moment of inertia around transversal axis in the second flight phase.

Keywords: *Code of Point, FIG, vault, men's artistic gymnastics, difficulty, biomechanics.*

INTRODUCTION

First ever uniform instructions on Code of Points (COP) in gymnastics under the International Gymnastics Federation (FIG) date back to 1949. The FIG technical committee improves and further develops the COP every four years. Many biomechanical researches have been conducted in the past by Soviet, German, American, Japan, English, Slovene and other researchers (e.g. Šlemin & Ukran, 1977; Gaverdovsky & Smolevsky, 1979; Brueggeman, 1994; Prassas, 1995; Krug, 1997; 1998; Takei, 1998; Čuk & Karácsony, 2004; Marinšek, 2010; Ferkolj, 2010) and knowledge of physical parameters of vaults are generally known. However, rules have not always followed the ever-changing nature of vaults since 1949. More specifically, rules have been late when it comes to the definition of the vault difficulty level. With inclusion of the saltos in the second flight phase, the vault difficulty becomes defined primarily by body position (tucked, piked or stretched) and the number of rotations around the transversal and longitudinal body axis in the first and second flight phase (COP FIG, 1964; 1971; 1978; 1985; 1989; 1993; 1997; 2001; 2006; 2009). Difficulty values (DV) have changed on the basis of the total number of rotations performed around transversal and longitudinal axis in the first and second flight phase (Table 1). Usually the COP rewarded each new vault with more DV, old vaults had to be awarded fewer DV although the vault remained the same.

The overview of changes and correlations between the DV, shown in (Table 2), illustrate that there have been no significant changes in the past years where correlations are rather high between the DV awarding rules that have been applied up to now. There is a big difference between a COP from 1964 to 2009 year where the correlations less than .47 percent.

Table 1. *Development of handspring style of vaults in COP (FIG) and their difficulty value.*

Year of publication (COP)	Tucked	Points	Piked	Points	Stretched	Points
1964					Forward handspring	10.00
1971	Handspring forward and salto forward tucked	10.00			Forward handspring with ½ turn	10.00
	Handspring forward and salto forward tucked with ½ turn (or Cuervo tucked)	9.8			Forward handspring with 1/1 turn	10.00
1985	Handspring forward and salto forward tucked with 1/1 turn	9.60	Handspring forward and salto forward piked	9.40	Forward handspring with 3/2 turn	9.40
			Handspring forward and salto forward piked with ½ turn	9.40	Handspring forward and salto forward stretched	9.60
					Handspring forward and salto forward tucked stretched with ½ turn (Cuervo stretched)	9.60
1989	Handspring forward and salto forward tucked with 3/2 turn	9.60	Handspring forward and salto forward piked with 3/2 turn	9.60	Forward handspring stretched with 2/1 turn	9.40
					Handspring forward and salto forward stretched with ½ turn (Kroll)	9.60
					Handspring forward and salto forward stretched with 3/2 turn (Lou Yun)	9.60
1993	Handspring forward and double salto forward tucked (Roche)	9.80				
	Handspring forward and double salto forward tucked with 1/2 turn (Xiao Jun Feng)	9.80				
1997					Handspring forward and salto forward stretched with 2/1 turn	10.00
					Handspring forward and salto forward stretched with 5/2 turn (Yeo 2)	10.00
2006	Handspring forward and salto forward tucked with 1/2 turn and salto backward tucked (Zimmerman)	7.0	Handspring forward and double salto forward piked (Blanik)	7.0		
			Handspring forward and double salto forward piked with ½ turn (Dragulescu)	7.2		

Table 2. *Correlations between COP (FIG) from 1964 to 2009.*

Year of publication	*2009-2006*	*2006-2001*	*2001-1997*	*1997-1993*	*1989-1985*	*1985-1978*	*1978-1971*	*1971-1964*	
R	1	0.994	0.932	0.890	0.872	0.875	0.946	0.976	
R^2	1	0.988	0.870	0.793	0.761	0.766	0.894	0.952	
	2006	*2001*	*1997*	*1993*	*1989*	*1985*	*1978*	*1971*	*1964*
R 2009	1	0.994	0.931	0.862	0.838	0.823	0.795	0.595	0.475
R^2 *2009*	1	0.988	0.866	0.744	0.703	0.678	0.632	0.355	0.225

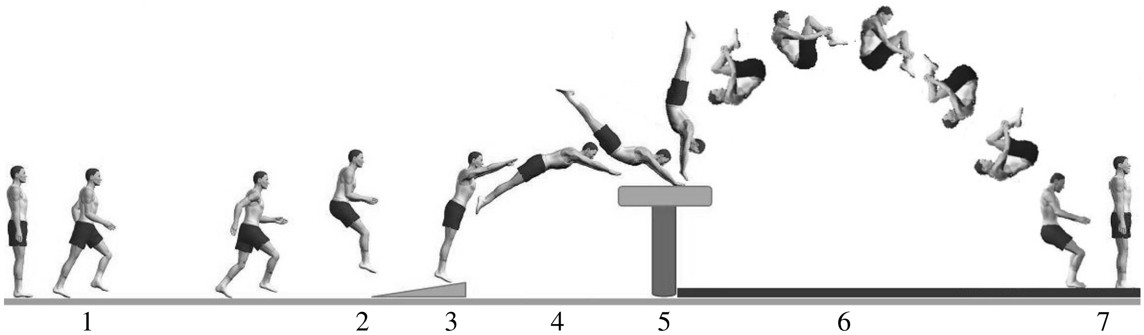


Figure 1. *Vault phases: 1-run, 2-jump on springboard, 3-springboard support phase, 4-first flight phase, 5-support on the table, 6-second flight phase, 7-landing.*

Each vault in COP can be divided in the following seven phases (Figure 1) (Prassas, 2002; Čuk & Karácsony, 2004; Takei, 2007; Ferkolj, 2010) run, jump on springboard, springboard support phase, first flight phase, support on the table, second flight phase, and landing.

According to the COP (FIG, 2009), the vault DV is already predetermined in the vault itself and is representative of the level degrees of turns around transversal and longitudinal axis in the first and second flight phase. The gymnast must show the intended body position (tucked, piked or stretched) in a distinct and unmistakable manner. Indistinct body positions are deducted by the E-Jury and may result in recognition as a lower value vault by the D-Jury. Table 3 shows that piked and stretched positions have no imapct on DV in sample handspring vaults, while within handsprings with saltos, a general rule appears. Vaults with piked position saltos in the second flight phase have 0.4 higher value than vaults with tucked position saltos; stretched position saltos have 0.8 higher value than piked position saltos. Every increase of 180 degrees turn around longitudinal axis in the second flight saltos adds 0.4 points to the vault DV.

Takei (1998) identified mechanical variables that govern the successful performance of a vault. The following were important determinants of success: large horizontal velocity, large horizontal kinetic energy, and overall translational kinetic energy at take-off from the board; short duration, small vertical displacement of body's center of gravity (BCG), and small somersaulting angular distance of preflight; large vertical velocity and large vertical kinetic energy at take-off from the horse; and large “amplitude of postflight,” that is, large horizontal and vertical displacements of BCG and long duration of flight; great height of BCG during the second quarter-turn in postflight; and small point deduction for landing.

Prassas (2002) schematically presented what vaulting success is dependent on and what the significant variables are. Some of them are independent and some are under the gymnastic control, such as: linear postflight displacment of

BCG, postflight somersaults/twist, linear momentum at vault take-off, duration of postflight, angular momentum at vault take-off, BCG vertical velocity, BCG position, linear at angular momentum at vault contact, change in linear and angular momentum on vault.

Table 3. *Development of handspring style of vaults in COP (FIG, 2009) and their DV.*

Hanpspring style vaults (III group)	**Tucked (points)**	**Piked (points)**	**Stretched (points)**
Forward handspring		3.0 Yamashita	3.0
Forward handspring with ½ trun		3.4	3.4
Forward handspring with 1/1 turn		3.8	3.8
Forward handspring with 3/2 turn		4.2	4.2
Forward handspring with 2/1 turn		4.6	4.6
Handspring forward and salto	3.8	4.2	5.0
Handspring forward and salto ½ turn (Cuervo)	4.2	4.6	5.4
Handspring forward and salto 1/1 turn (Cuervo with ½ turn)	4.6	5.0	5.8
Handspring forward and salto 3/2 turn (Cuervo with 1/1 turn)	5.0 Kroll	5.4	6.2 Lou Yun
Handspring forward and salto 2/1 turn (Cuervo with 3/2 turn)	5.4 Canbass		6.6
Handspring forward and salto 5/2 turn (Cuervo with 2/1 turn)			7.0 Yeo 2
Handspring forward with 1/1 turn and salto forward	5.4 Behrend	5.8 Rehm	
Handspring forward and salto tucked with ½ turn and salto backward tucked	7.0 Zimmerman		
Handspring double salto forward	6.6 Roche	7.0 Blanik	
Handspring forward and double salto ½ turn	7.0	7.2 Dragulescu	

Schwiezer (2003) found which mechanical variables are important for optimal vault performance: positions of the hands on the table, reaction forces during the support phase of the hands, landing distances behind the table, run velocity, where the gymnast hits the vaulting board, distance of the vaulting board from vault, duration of first and second flight phase.

Čuk & Karacsony (2004) presented biomechanical characteristics of vaulting and the most important factors for successful vault jump e.g. (mophologic characteristics, run velocity, length of flight on the springboard, duration of board contact, position of feet from springboard edge, duration of 1st flight phase, duration of support on table phase, duration of 2nd flight phase, height of jump, moment of inertia in x and y axis, distance from take-off 2nd flight phase, landing).

Čuk, Bricelj, Bučar, Turšič, & Atiković (2007) researched relations between start value (SV) of vault and runway velocity in top level male artistic gymnasts. They found correlation between runway velocity and SV with all gymnasts included competing at World Championship (WC) 1997 in Lausanne (N=204). Correlation coefficient was 0.51, which means that runway velocity and SV share 25% variance, which is very low (for example – handspring salto forward tucked can be done with a large range of runway velocity). When vaults were grouped (e.g. average velocity for each vault - handspring salto tucked forward) and only average runway velocity per vault was considered, the correlation between vault runway velocity and SV was much higher with value of 0.70 and shared a variance of 49%, when vault SV from COP (FIG, 1997) were used and shared a variance of 53% when the COP (FIG, 2006) vault SV were used. . With the new philosophy of open ended COP, a new problem appeared: according to the COP (FIG, 2006), the apparatus are no longer equal.

Čuk & Atiković (2009), using a sample of 44 gymnasts who competed in all-around competition at the in Beijing 2008 Olympic Games (OG), found equality among apparatus scores. Equality was tested for using the achieved A scores of all MAG apparatus. Vault has the highest A scores, while pommel horse the lowest A scores. T-tests showed that those two apparatus significantly differed from other apparatus A scores by an average of 0.4 points. Factor analysis extracted 3 factors, with 67% of explained variance. On the 3rd factor, vault on positive side and pommel horse on the negative side were loaded. According to philosophy of the COP, the defined criteria for calculation of vault difficulty values, biomechanical characteristics of the vaults are important in evaluating the DV.

Čuk & Forbes (2010) investigated the implications of the difficulty scores in relation to the success in all-around competition on a sample of 49 all-around male gymnasts at the 2009 European Championships. For all-around results, the D scores of the six apparatus are not equivalent with the COP (FIG, 2009): the vault and the pommel horse D scores significantly differed from other apparatus. With the COP (FIG, 2009), the vault D scores do not discriminate between all-around gymnasts and all-around gymnasts have the lowest D scores on pommel horse.

There are many studies reporting on vault run speeds – maximum speed on springboard, first and second flight phase (Sands & McNeal, 1995; Krug, 1997; Čuk & Karácsony, 2004; Takei, 2007; Čuk et al., 2007; Naundorf, Brehmer, Knoll, Bronst & Wagner, 2008; Ferkolj, 2010; Veličković, Petrović & Petrović, 2011). According to the philosophy of COP, the defined criteria for calculation of vault difficulty values, biomechanical characteristics of the vaults are important to evaluate the DV values. The aim of this paper is to find which biomechanical parameters explain and define the initial vault DV.

METHODS

The study sample included 64 vaults out of the possible 115 listed in the COP (FIG, 2009), from which we obtained data from the researches conducted to date. In collecting the data, we could not use all vaults because some of them, for example, second group vaults, have not been performed in the last 20 years. Analyzing all reading materials and video recordings from large world competitions, men perform some 30 different vaults, accounting for quarter of all vaults. A total of 64 different vaults have been collected with 12 variables. The sample of dependent variables includes difficulty values (COP) ranging from 2 to 7.2 points, while the sample of independent variables include biomechanical variables shown in (Table 4).

The sample of independent variables are: degrees of turns in x and y axis in first and second flight phase (variable names: alpha in the x and y axis – the first and the second flight phase), shown on the basis of the COP (FIG, 2009) and defined by the quantity of rotations. The moment of inertia (*J*) was calculated by cylindric model of Petrov & Gagin (1974) ($J=ml^2/12$) for the first and second flight phases and the moment of inertia in x and y axis (Table 5). Moment of inertia was calculated by above formula where (l) is the distance between lower and higher point of the body (for x axis) or distance between most left and right point of the body (for y axis). To calculate (l) we used morphologic data of vault specialists body height 1.6735 m and body mass 68.15 kg by Čuk & Karácsony (2004) within the Dempster body model (by Winter, 1979) and g=9.81 m/s^2.

Duration parameters included: vault run speeds – maximum speed on springboard, first and second flight phase and duration of support on table phase determined as the average value from all vaults were calculated from elite gymnasts (N=230) performing at the 2006 WC in Aarhus, Denmark after analyzing video recordings from FIG (IRCOS-Instant Replay and Control System) as recorded at 50 frames per second (fps). BCG velocity on springboard, duration of the first and the second flight phases and duration of support on table phase are obtained from former studies (Sands & McNeal, 1995; Krug, 1997; Čuk & Karácsony, 2004; Takei, 2007; Čuk et al., 2007; Naundorf, Brehmer, Knoll, Bronst & Wagner, 2008; Ferkolj, 2010; Veličković, Petrović & Petrović, 2011).

Velocities of the dash are obtained from former researches, and body postures and moments of inertia in previously mentioned phases are taken as a model for all vaults. Average body positions and medium value, which were based on former studies, were taken in the phase of support on the table at group vaults. In terms of simplification of the model, only one value for an individual group of vaults was taken because we know that a vault can be performed in different positions (e.g. handspring forward and salto forward), and can be performed either with the presented position in support on the table or with the higher position in the moment of support on the table. Duration "time" variables are also calculated based on previous studies and on the IRCOS WC 2009. It would be good to make a 3-D kinematic analysis for every vault, but for this type of research, we mention in the subject and in the problem, the individual jumps are difficult to collect because they havenot been performed for many years. Only ¼ of the total number of vaults from COP (FIG, 2009) are being performed at competitions. Due to the fact that we do not have all information about all the vaults, simplifications were needed in order to increase generalization, especially in the field of calculating position of the body for groups of vaults.

Data were processed as follows: in analyzing descriptive parameters of variables applied in vaults, Kolmogorov-Smirnov test to determine the normality of distribution of the results for further multivariate analysis, Pearson correlations, regression analysis with vault DV as criteria and selected biomechanical variables as predictors (according to the method entered). For the significance of the regression analysis, F test was used. As vaults are continuous actions where vault phases build on one another, we therefore selected only independent variables (a variable can not be a mathematical function of two or more known variable, as the variablility of such varibles do not bring any new variance). For that reason specifically, the analysis included the trajectory, the moment of inertia and individual vault phase times. We took into consideration correlations and multiple correlations at the significance level of $p<0.05$.

RESULTS AND DISCUSSION

The deterministic model of attempted clarification of vault values with biomechanical parameters in the men's artistic gymnastics was presented by descriptive parameters, significant correlations between 12 variables, and interpretation of results are presented into this section. The analysis and discussion begin with variables of 64 vaults, moments of inertia for various body positions in the first and second flight phases, Pearson correlation matrix, the regressive analysis of the criteria variable from the COP (FIG, 2009) and the impact of individual variables on the criteria variable.

In the correlations matrix (Table 6), criteria variables from the COP (FIG, 2009) effected a statistically significant correlation with five variables: BCG velocity on springboad (r: 0.768, $p<0.05$), alpha in x axis 2nd flight phase (r: 0.759, $p<0.05$), time of 2nd flight phase (r: 0.646, $p<0.05$), time of 1st flight phase (r: -0.486, $p<0.05$) and alpha in y axis 2nd flight phase (r: 0.359, $p<0.01$). The reason for the relation between BCG velocity on the springboard and vault DV is that velocity on springboard proportionally increases from 6.0 m/s (Stoop) to 10.9 m/s (Dragulescu piked) as the vault's DV increases from 2.0 points (Stoop) to 7.2 points (Dragulescu piked). With higher velocity on the springboard (m/s), gymnasts increase the 2nd flight duration (s) and it allow them to perform a greater amount of rotation around the x body axis during the 2nd flight phase (range from 120 degrees (Stoop) to 900 degrees (Handspring forward and double somersault forward tucked) and consequently increase the vault's DV. The longer the duration of the flight time of the gymnast is during the 2nd flight phase ranging from 0.7 s (Handspring sideway with ¼ turn; DV: 3.0) to 1.2 s (Handspring sideway with ¼ turn the somersault forward piked; DV: 4.2), the vault's DV increases.

In Table 7, the predictor system of variables (R Square) explains 92% of the common variables with criteria, while the correlation of the entire predictor system of variables with criteria, the coefficient of multiple correlation amounts to 0.96 (RO).

Table 4. *Values of selected variables of I, III, IV and V groups (N=64 vaults)*

Ordinal number of jumps	Terminological description of the jump	Code of Points - FIG, 2009. (points)	BCG velocity on springboard (m/s)	Time of first flight phase (s)	Time of second flight phase (s)	Time of support on the table (s)	Alpha in x axis second flight phase (°)	Alpha in y axis second flight phase (°)	Alpha in x axis first flight phase (°)	Alpha in y axis first flight phase (°)	Moment of inertia J in x axis 1.f.p. ($kgms^2$)	Moment of inertia J in y axis 1.f.p. ($kgms^2$)	Moment of inertia J in x axis 2.f.p. ($kgms^2$)	Moment of inertia J in y axis 2.f.p. ($kgms^2$)
1.01	Stoop	2.0	6.00	0.30	0.75	0.12	120	0	120	0	1.706	0.000	0.738	0.000
1.02	Stoop with ½ t.	2.0	6.21	0.31	0.80	0.13	120	180	120	0	1.706	0.000	0.738	0.127
1.07	Hecht	2.2	6.80	0.32	0.84	0.14	120	0	120	0	1.706	0.000	1.731	0.000
1.08	Hecht with ½ t.	3.0	6.60	0.33	0.89	0.14	120	180	120	0	1.706	0.000	1.731	0.127
1.09	Hecht with 1/1 t.	4.2	7.00	0.32	0.86	0.14	120	360	120	0	1.706	0.000	1.731	0.127
1.10	Hecht with 3/2 t.	5.0	6.70	0.33	0.90	0.13	120	540	120	0	1.706	0.000	1.731	0.127
1.11	Hecht with 2/1 t.	5.4	7.33	0.32	0.84	0.15	120	720	120	0	1.706	0.000	1.731	0.127
3.01	Forward handspring	3.0	6.95	0.26	0.70	0.15	180	0	160	0	1.771	0.000	1.731	0.000
3.02	Forward handspring with ½ t.	3.4	7.10	0.27	0.71	0.21	180	180	160	0	1.771	0.000	1.731	0.127
3.03	Forward handspring with 1/1 t.	3.8	7.50	0.28	0.85	0.28	180	360	160	0	1.771	0.000	1.731	0.127
3.04	Forward handspring with 3/2 t.	4.2	7.60	0.29	0.74	0.24	180	540	160	0	1.771	0.000	1.731	0.127
3.05	Forward handspring with 2/1 t.	4.6	8.00	0.30	0.75	0.26	180	720	160	0	1.771	0.000	1.731	0.127
3.13	Handspring fwd. and salto fwd. t.	3.8	7.20	0.24	0.92	0.16	540	0	160	0	1.771	0.000	0.458	0.000
3.14	Hdspr. fwd. and salto fwd. t. w. ½ t. (or Cuervo t.)	4.2	7.50	0.16	0.96	0.15	540	180	160	0	1.771	0.000	0.458	0.127
3.15	Hdspr. fwd. and salto fwd. t. w. 1/1 t. (Cuervo t. w. ½ t.)	4.6	8.20	0.17	0.97	0.12	540	360	160	0	1.771	0.000	0.458	0.127
3.16	Hdspr. fwd. and salto fwd. t. w. 3/2 t. (Cuervo t. w. 1/1 t.)	5.0	8.60	0.17	0.98	0.14	540	540	160	0	1.771	0.000	0.458	0.127
3.19	Handspring fwd. and salto fwd. p.	4.2	7.50	0.28	0.90	0.16	540	0	160	0	1.771	0.000	0.458	0.127
3.20	Hdspr. fwd. and salto fwd. p. w. ½ t. (Cuervo p.)	4.6	8.03	0.22	0.91	0.16	540	180	160	0	1.771	0.000	0.738	0.127
3.21	Hdspr. fwd. and salto fwd. p. w. 1/1 t. (Cuervo p. w. ½ t.)	5.0	8.56	0.20	0.98	0.12	540	360	160	0	1.771	0.000	0.738	0.127
3.26	Hdspr. fwd. w. 1/1 t. and salto fwd. p. (Rehm)	5.8	7.70	0.08	1.00	0.12	540	360	160	0	1.771	0.000	0.738	0.127
3.31	Handspring fwd. and salto fwd. str.	5.0	7.95	0.24	0.88	0.12	540	0	160	0	1.771	0.000	1.731	0.000
3.32	Hdspr. fwd. and salto fwd. str. w. ½ t. (Cuervo str.)	5.4	8.00	0.16	0.84	0.24	540	180	160	0	1.771	0.000	1.731	0.127
3.33	Hdspr. fwd. and salto fwd. str. w. 1/1 t. (Cuervostr. ½ t.)	5.8	8.05	0.17	0.91	0.19	540	360	160	0	1.771	0.000	1.731	0.127

3.34	Hdspr. fwd. and salto fwd. str. w. 3/2 t. (Cuervostr. w. 1/1 t.) (Lou Yun)	6.2	8.30	0.17	0.98	0.14	540	540	160	0	1.771	0.000	1.731	0.127
3.35	Hdspr. fwd. and salto fwd. str. w. 2/1 t. (Cuervostr. 3/2 t.)	6.6	8.60	0.16	0.96	0.16	540	720	160	0	1.771	0.000	1.731	0.127
3.36	Handspring fwd. and salto fwd. str. w. 5/2 t. (Yeo 2)	7.0	8.90	0.16	1.08	0.12	540	900	160	0	1.771	0.000	1.731	0.127
3.37	Handspring fwd. and dbl. salto fwd. t. (Roche)	6.6	8,23	0.18	1.09	0.11	900	0	160	0	1.771	0.000	0.458	0.000
3.38	Roche with 1/2 turn (Dragulescu)	7.0	10.50	0.16	1.12	0.12	900	180	160	0	1.771	0.000	0.458	0.127
3.39	Handspring fwd. and salto fwd. t. w. ½ t. andsalto bwd. t. (Zimmerman)	7.0	10.50	0.20	1.12	0.12	900	180	160	0	1.771	0.000	0.458	0.127
3.40	Handspring fwd. and dbl. salto fwd. piked. (Blanik)	7.0	10.00	0.24	1.08	0.08	900	0	160	0	1.771	0.000	0.738	0.000
3.41	Dragulescu piked.	7.2	10.90	0.14	1.15	0.13	900	180	160	0	1.771	0.000	0.738	0.127
4.01	Handspring sw. with ¼ t.	3.0	7.25	0.15	0.70	0.09	180	90	160	0	1.874	0.555	1.731	0.127
4.02	Handspring sw. with 3/4 t.	3.4	7.43	0.18	0.73	0.10	180	360	90	90	1.874	0.555	1.731	0.127
4.03	Handspring sw. with 5/4 t.	3.8	7.60	0.20	0.75	0.12	180	610	90	90	1.874	0.555	1.731	0.127
4.04	Hdspr. sw. with. ¼ t. a. salto fwd. t.	3.8	7.65	0.18	1.18	0.10	540	90	90	90	1.874	0.555	0.458	0.127
4.05	Handspring sw. w. ¼ t. a. salto fwd. p.	4.2	7.90	0.20	1.02	0.11	540	90	90	90	1.874	0.555	0.738	0.127
4.07	Handspring sw. w. ¼ t. a. salto fwd. str.	5.4	8.00	0.19	1.20	0.10	540	90	90	90	1.874	0.555	1.731	0.127
4.13	Handspring sw. w. ¼ t. a. salto bwd. t. (Tsukahara)	3.8	7.00	0.16	0.98	0.18	540	90	90	90	1.874	0.555	0.458	0.127
4.14	Tsukahara t. with ½ t.	4.2	7.20	0.16	1.00	0.16	540	270	90	90	1.874	0.555	0.458	0.127
4.15	Hdspr. sw. w. ¼ t. a. salto fwd. t. w. ½ t. (Kasamatsu)	4.6	7.20	0.14	0.88	0.22	540	450	90	90	1.874	0.555	0.458	0.127
4.17	Tsukahara t. with 2/1 t. (Barbieri)	5.4	7.60	0.12	1.04	0.22	540	810	90	90	1.874	0.555	0.458	0.127
4.19	Tsukahara piked	4.0	7.37	0.14	0.88	0.16	540	990	90	90	1.874	0.555	0.738	0.127
4.21	Tsukahara p. with 1/1 t.	4.8	7.51	0.12	0.96	0.20	540	450	90	90	1.874	0.555	0.738	0.127
4.25	Tsukahara stretched	4.6	7.65	0.14	0.85	0.26	540	90	90	90	1.874	0.555	1.731	0.127
4.26	Tsukahara str. with ½ t.	5.0	7.40	0.12	0.92	0.24	540	270	90	90	1.874	0.555	1.731	0.127
4.27	Tsukahara str. w. 1/1 t. or Kasamatsu str.	5.4	7.93	0.14	0.87	0.24	540	450	90	90	1.874	0.555	1.731	0.127
4.28	Kasamatsu str. with 1/2 t. or Tsukahara str. w. 3/2 t.	5.8	8.04	0.13	0.87	0.23	540	630	90	90	1.874	0.555	1.731	0.127
4.29	Kasamatsu str. w. 1/1 t. or Tsukahara str. w. 2/1 t. (Akopian)	6.2	8.13	0.14	0.96	0.21	540	810	90	90	1.874	0.555	1.731	0.127
4.30	Kasamatsu str. with 3/2 t. (Driggs)	6.6	8.50	0.14	0.98	0.19	540	990	90	90	1.874	0.555	1.731	0.127
4.31	Kasamatsu str. with 2/1 t. (Lopez)	7.0	8.87	0.16	1.00	0.16	540	1170	90	90	1.874	0.555	1.731	0.127
4.37	Tsukahara with salto bwd. t. (Yeo)	6.6	8.80	0.12	1.00	0.20	900	90	90	90	1.874	0.555	0.458	0.000
4.43	Tsukahara with salto bwd. piked. (Lu Yu Fu)	7.0	9.10	0.16	1.04	0.17	900	90	90	90	1.874	0.555	0.738	0.000
5.17	Yurchenko and salto bwd. t. (Melissanidis)	7.0	8.74	0.16	1.06	0.14	900	0	160	0	1.145	0.000	0.738	0.000

5.19	Yurchenko stretched	4.6	7.10	0.16	0.84	0.20	540	0	160	0	1.145	0.000	1.731	0.000
5.20	Yurchenko stretched with ½ t.	5.0	7.23	0.16	0.88	0.19	540	180	160	0	1.145	0.000	1.731	0.127
5.21	Yurchenko stretched with 1/1 t.	5.4	7.30	0.16	0.92	0.18	540	360	160	0	1.145	0.000	1.731	0.127
5.22	Yurchenko stretched with 3/2 t.	5.8	7.37	0.17	0.93	0.15	540	540	160	0	1.145	0.000	1.731	0.127
5.23	Yurchenko stretched with 2/1 t.	6.2	7.33	0.18	0.99	0.13	540	720	160	0	1.145	0.000	1.731	0.127
5.25	Yurchenko stretched with 5/2 t. (Shewfelt)	6.6	7.44	0.15	1.01	0.13	540	900	160	0	1.145	0.000	1.731	0.127
5.33	Round off, ½ t. and hdspr. fwd. with ½ t.	3.6	7.20	0.16	0.86	0.14	180	180	160	180	1.978	0.127	1.731	0.127
5.35	Round off, ½ t. and hdspr. fwd. with 1/1 t.	4.0	7.00	0.17	0.97	0.13	180	360	160	180	1.978	0.127	1.731	0.127
5.50	Round off, ½ t. and hdspr. fwd. a. salto fwd. str. w. ½ t. (Hutcheon)	5.6	7.53	0.16	0.88	0.12	540	180	160	180	1.978	0.127	1.731	0.127
5.55	Round off, ½ t. and hdspr. fwd. a. salto fwd. str. w. 5/2 t. (Li Xiao Peng)	7.2	8.23	0.20	0.96	0.08	540	900	160	180	1.978	0.127	1.731	0.127
5.79	Round off, jump bwd w. 1/1 t. to back hdspr. a. salto bwd. str. (Scherbo)	5.0	8.22	0.20	0.84	0.20	540	0	160	360	1.978	0.127	1.731	0.000

Table 5. *Moments of inertia as calculated for various body positions in first and second flight phases.*

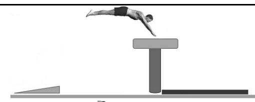
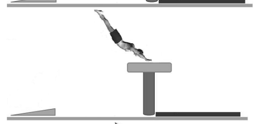
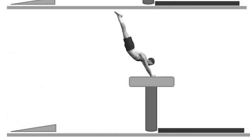
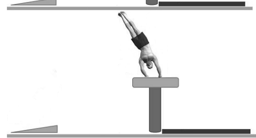
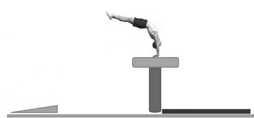
Values calculated as per the model (J/g)	Body axis	Figure	Groups of vaults and body position in flight phase
1.706	x		I – Direct vaults
1.978	x		II – Vaults with full turns in first flight phase
1.771	x		III – Front handspring and (Yamashita style vaults)
1.874	x		IV – Vaults with 1/4 turn in first flight phase (Tsukahara & Kasamatsu)
1.145	x		V – Round-off entry vaults (Yurchenko, Nemov & Sherbo)
0.458	x		Tucked
0.738	x		Piked
1.731	x		Stretched
0.127	y		Shoulder width
0.555	y		Arch-like position in group IV vaults

Table 6. *Correlation matrix.*

Variable	COP, FIG, 2009. (points)	BCG velocity on springboard (m/s)	Time of first flight phase (s)	Time of second flight phase (s)	Time of support on the table (s)	Alpha in x axis second flight phase (°)	Alpha in y axis second flight phase (°)	Alpha in x axis first flight phase (°)	Alpha in y axis first flight phase (°)	Moment of inertia J in x axis 1.f.p. (kgms^2)	Moment of inertia J in y axis 1.f.p. (kgms^2)	Moment of inertia J in x axis 2.f.p. (kgms^2)	Moment of inertia J in y axis 2.f.p. (kgms^2)
Code of Points – FIG, 2009. (points)	1	**.768***	**-.486***	**.646***	-0.052	**.759***	**.359****	0.135	0.026	-0.14	-0.02	-0.02	0.014
BCG velocity on springboard (m/s)		1	**-.349***	**.614***	-0.14	**.748***	0.067	0.171	-0.028	0.132	-0.028	**-.261***	-0.043
Time of first flight phase (s)			1	**-.413***	-0.101	**-.609***	-0.19	0.175	**-.320***	-0.033	**-.480***	0.167	-0.17
Time of second flight phase (s)				1	**-.336***	**.738***	0.036	-0.057	0.019	-0.023	0.084	**-.461***	0.034
Time of support on the table (s)					1	-0.071	0.132	-0.207	0.092	0.021	0.202	0.208	0.103
Alpha in x axis second flight phase (°)						1	-0.116	0.046	0.035	-0.096	0.11	**-.495***	-0.225
Alpha in y axis second flight phase (°)							1	-0.186	0.067	0.003	0.181	**.304***	**.524***
Alpha in x axis first flight phase (°)								1	**-.366***	**-.372***	**-.870***	0.096	-0.119
Alpha in y axis first flight phase (°)									1	**.502***	**.528***	0.119	0
Moment of inertia J in x axis 1.f.p. (kgms^2)										1	**.452***	-0.149	0.119
Moment of inertia J in y axis 1.f.p. (kgms^2)											1	-0.079	0.167
Moment of inertia J in x axis 2.f.p. (kgms^2)												1	0.156
Moment of inertia J in y axis 2.f.p. (kgms^2)													1

*. Correlation is significant at the 0.05 level (2-tailed).

Table 7. *The regressive analysis of the criteria variable COP (FIG, 2009),*

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.961[a]	.924	.906	.418	.924	51.768	12	51	.000

Table 8. *The impact of individual variables on the criteria variable COP (FIG, 2009).*

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	95,0% Confidence Interval for B Lower Bound	95,0% Confidence Interval for B Upper Bound
1	(Constant)	-2.063	1.410		-1.463	.150	-4.894	.768
	Code of Points – FIG, 2009. (points)	.219	.120	.151	1.832	.073	-.021	.459
	BCG velocity on springboard (m/s)	.941	1.731	.043	.543	.589	-2.535	4.416
	Time of first flight phase (s)	1.418	.886	.121	1.599	.116	-.362	3.197
	Time of second flight phase (s)	-.679	1.355	-.024	-.501	.619	-3.400	2.042
	Time of support on the table (s)	.005	.001	.835	6.638	.000	.003	.006
	Alpha in x axis second flight phase (°)	.002	.000	.375	7.308	.000	.001	.002
	Alpha in y axis second flight phase (°)	-.003	.005	-.066	-.583	.562	-.012	.007
	Alpha in x axis first flight phase (°)	.000	.001	.007	.128	.899	-.002	.002
	Alpha in y axis first flight phase (°)	.300	.381	.049	.787	.435	-.465	1.065
	Moment of inertia J in x axis 1.f.p. ($kgms^2$)	-1.116	.689	-.211	-1.621	.111	-2.498	.266
	Moment of inertia J in y axis 1.f.p. ($kgms^2$)	.888	.137	.373	6.489	.000	.613	1.163
	Moment of inertia J in x axis 2.f.p. ($kgms^2$)	-.544	1.481	-.020	-.367	.715	-3.517	2.430

The analysis of the impact of individual variables in Table 8 showed that the highest and statistically most important influence of the criteria variables from the COP are with the following individual variables: alpha x in the 2nd flight phase (Beta: 0.835, sig.<0.001), alpha y in the 2nd flight phase (Beta: 0.375, sig.<0.001) and the moment of inertia Jx in the 2nd flight phase (Beta: 0.373; sig.<0.001). Prediction was significantly correlated with only three variables, meaning that the present vault difficulties COP (FIG, 2009) are defined by these three variables of the 2nd flight phase. The regressive analysis clearly shows that the initial value prediction is very high. Degrees of turns around transversal and longitudinal axis, and body position in the 2nd flight phase are the only predictors and the most significant predictors in the COP (FIG, 2009). It can be noted that the FIG Technical Committee only considered the 2nd flight phase starting with the table take-off onwards to just before landing. Hence, the 5 different vaults to support on the apparatus have no significant prediction to initial jump difficulty level. While Pearson correlation between DV value and BCG velocity on the springboard is the highest in regression analysis (r: 0.768, p<0.05), the variance of the velocity is related to other parameters, probably mostly to alpha x in 2nd flight phase (r: 0.759, p<0.05).

Bruggemann (1987) and Kwon (1996) noted that the DV is often increased by adding more rotations of somersaults into its basic form. Bruggemann (1987) reviewed the research literature on gymnastics vaulting, based largely on his work on continous rotation vaults. He reported that the higher skilled gymnasts were better able to increase the linear and angular moment at horse take-off than the lower skilled gymnasts. He concluded that approach velocity was of high significance to the overall preformance of vault. It would appear that the success of a vault could be attributed to a large extent to the 1st flight phase characteristics. However, Bruggemann (1994) noted that the purpose of 2nd flight phase is to alter the 1st flight phase. This is established by generating lift through a higher vertical velocity and maintaining sufficient momentum for the postflight since the main goal of the vault is to establish height and distance in the second flight phase, which contains the actual difficulties of the vault.

Takei, Blucker, Nohara & Yamashita (2000) used correlation analysis to establish the strength of the relationship between the causal mechanical variables identified in the model and the judges' scores. From the 18 significant variables identified in the present study, the angular distance of 1st and 2nd flight phases, the horizontal velocity and angular momentum at take-off from the horse, and the average moment of inertia and duration of 2nd flight phase collectively accounted for 57% of the variation in the judges' scores. Continuation of the vault and the results are meaningful when viewed together with the continued movement of the vault in performance as a second flight phase follows. This can be explained if the biomechanical aspects of the more demanding first flight phase of the jump in terms of modes of movement (direction, rotation, body's positions, the phases of flight). The gymnast must be, for a very short period of time, prepared for the continuation of the vault. Takei (2007) in his handspring double salto forward tucked study analyzed the strength of the relationship between the mechanical variables identified and the judges' scores. Significant correlations indicated that the higher judges' scores were negatively related to five mechanical variables and positively related to seventeen variables in the model. The normalized horizontal displacement of body center of mass (BCM) from the knee grasp to the peak of 2nd flight phase was the best single predictor of the judges' score and accounted for 50% of variation in the judges' score. The landing point deductions and the official horizontal distance of 2nd flight phase collectively accounted for 86% of the variance in the judges' scores.

The regression analysis results lead us to the conclusion that members of the FIG men's technical committee had in mind a simple model of the COP, which would easily determine the vault difficulty level. The present vault DV model of the COP (FIG, 2009) is not too complicated, however it obviously does not differentiate difficulty among vault groups and their most important biomechanical components.

CONCLUSIONS

Bearing in mind the results, one could make a better model of determining the DV of a vault. In future analysis, it would first be necessary to establish latent dimensions that can define the vaults and followed by a factor analysis of whether the vaults are explained only with three variables from the manifest variable space (degrees of turns around transversal axis, degrees of turns around longitudinal axis and body's and moment of inertia around transversal axis in second flight phase). From the factor analysis, we could determine independent factors that define the vaults and, with the results of the factor analyzeis, it would be possible to propose better evaluation of the vault difficulty.

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