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ORIGINAL

Three-dimensional Kinematic Analysis of the Yurchenko Layout with 360-degree Twist in Female Vaults: Deterministic Model and Judges' Scores

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Objective: The purpose of this study was to identify kinematic variables that govern successful performance and judges' scores and to establish correlative relationships among those of Yurchenko layout with a full twist in female vaults.

Method: Four video cameras with sampling rate of 60 Hz collected 32 motion data of Yurchenko vaults from twenty-two female participants (age: 18.6 ± 3.6 years, height: 153.0 ± 6.5 cm, mass: 44.7 ± 7.3 kg) during national competition. Posting processing and calculations of kinematic variables were performed in Kwon 3D XP and Matlab® programs. Correlation and regression analyses were applied to find the relationships between the obtained scores and kinematic variables. Deterministic model (Hay & Reid, 1988) was used to investigate the strength of correlative relationships among kinematic variables.

Results: The obtained scores from the judges' decision were mainly affected by post-flight peak height, horse contact time, knee angle at landing, and horse takeoff angle. Strong blocking during horse contact was required to get successful performance and obtain high scores. Modified deterministic model showed that round-off entrance and takeoff angles and resultant velocity of the center of mass (CM) during the round-off phase were the starting variables affecting performance in the following kinematics. Knee angle at landing, a highly influential variable on the obtained point, was only determined by judges' decision without significant correlative relationship with previous kinematic variables.

Conclusion: The obtained scores highly depended on kinematic variables of post-flight and horse contact phases that were affected by those from the previous phases including round-off postures and resultant velocity of the body center of mass.

Keywords: Kinematics, Yurchenko, Obtained point, Deterministic model

INTRODUCTION

The Yurchenko vault was first introduced by Natalia Yurchenko, a Soviet gymnast, in the 1982 World Cup (Carlton, 1988; Langsley, 1983). It comprises a round-off entry onto the springboard, followed by a back handspring with turns onto the vault table for the post-flight (Yoon, 2003). Since its introduction, numerous female gymnasts have attempted to master this technique, with 89 out of 149 vault techniques being the Yurchenko vault in the 1988 Seoul Olympics (Kwon, Fortney, & Shin, 1990). However, some athletes avoided this technique at that time due to a high risk of injury, as the horizontal configuration of the old vaulting horse created little space for hand contact and the back handspring entry onto the horse gave the gymnast no visual approach to the contact area. The change to the new vaulting horse increased the horse contact area, rapidly popularizing the Yurchenko vault. Currently, it accounts for more than 70% of the vaults performed by female athletes in international competitions, and it has become a comparably essential technique among female athletes in national competitions in Korea as well (Kim & Kim, 2011; Yeo, Kim, & Kim, 2011). One reason behind its popularity among female athletes is speculated to be that it is easier to create angular momentum in the sagittal plane with the Yurchenko vault than with other techniques, thereby being more useful for female athletes, who tend to have weaker blocking on the horse (Park & Kim, 2016).

In the early stages, simple Yurchenko layout vaults were the most popular, but Yurchenko layout vaults with a twist began to gain popularity. Athletes performed layouts with 360° twist to even 720° or greater twist; in 2016 Rio Olympic Games, Simone Biles, a US gymnast, earned the gold medal with a Yurchenko layout with a 900° twist (Park & Kim, 2016; Seo, 2016; Yeo, 2006). Unfortunately, however, Korean female gymnasts mostly perform a 360° twisting layout, which corresponds to 5.0 points in the International Federation of Gymnastics (FIG) code of point, widening the technical competency gap from world-class competitors (FIG, 2013). Particularly, there has been no Korean female vault medalist in international competitions since Park Ji-Suk (Bronze medal, 1990 Beijing Asian Games), alluding to the standstill status of Korea's women's vault. Therefore, a kinematic study was demanded to enhance Korean female athletes' technical proficiency of the Yurchenko vault.

Foreign studies on the Yurchenko vaults mainly involved kinematic analysis and computer simulations (Koh & Jennings, 2003, 2007; Koh, Jennings, & Elliott, 2003; Kwon et al., 1990; Seeley & Bressel, 2005). In a comparison of Yurchenko stretched salto and Yurchenko layout with 360° twist, Kwon et al. (1990) showed that twisting technique has shorter board and horse contact and longer post-flight duration than simple layout. Furthermore, they stated that minimizing the loss of vertical horse takeoff speed is important for a successful performance. In their interpretation of dynamic simulations, Koh and Jennings (2003) reported that increasing the vertical horse takeoff speed, horse entrance angle, and pre-flight angular momentum are crucial for a successful stretched salto. However, in a subsequent study (Koh & Jennings, 2007), they argued that increasing pre-flight angular momentum is impractical, while increasing the horse entrance angle is more practical.

Korean studies on the Yurchenko vault have performed various kinematic analyses for both male and female athletes (Park & Kim, 2016; Song, Kim, & Moon, 2015; Yeo, 2006a, 2006b; Yeo et al., 2011; Yoon, 2003; Yoon & Kim, 2006a, 2006b; Yoon & Min, 2011; Yoon, Min, Hah, Park, & Lee, 2008). Yeo (2006a, 2006b) analyzed men's Yurchenko vault with a 720° and 900° twists and showed that high scorers displayed shorter horse contact time and faster vertical horse takeoff than low scorers. They insisted the need of good blocking to achieve proficient outcomes, but their study did not include female athletes. Although Park and Kim (2016), Yoon and Min (2011), and Yoon et al. (2008) performed studies on female athletes, these involved simple comparisons of kinematic variables between experts and beginners and between high scored and low scored groups. These findings offer limited practical information for coaches and have shortcomings in comprehensively assessing the sequential motions in a vault.

Kinematic knowledge has been qualitatively systemized and deterministic model theory has been developed for application in various sports (Hay & Reid, 1988). A deterministic model provides a comprehensive understanding of the variables that affect performance by determining how much each linear and angular motion variable contributes to the final goal (game record or score) and how they are related to one another. In gymnastics, Takei (1989, 1991, 1998, 2007) and colleagues (Takei, Blucker, Nohara, & Yamashita, 2000; Takei, Dunn, & Blucker, 2007) analyzed the handspring, Roche, and Hetch techniques with a deterministic model and discovered kinetic and kinematic variables that influence performance scores and defined the relationships among the variables. One common finding was that post-flight performance has huge influence on the final score. However, no study has applied a deterministic model on the Yurchenko vault in female athletes. Due to the sequential nature of vault kinematics that occur in a very short time (within two seconds), it is substantially impossible for the athlete to use his/her kinesthetic feedback and adjust the kinematic variables in the middle of the vault; hence, knowing how kinematics in the preceding phase affect subsequent phases is highly important. Landing performance in vaulting is affected by post-flight, post-flight performance by horse contact, and horse contact by pre-flight. Hence, searching for the variables in preceding phases that affect performance ultimately leads to the kinematic variables that influence the first run-on.

The aim of this study were to provide practical implications for coaches by analyzing judges' scores and kinematic variables in the Yurchenko layout with a 360° twist in women's vault in a national competition and to apply the deterministic model in attempt to identify their associations with the kinematic variables of the preceding phases. We hypothesized that the variables identified through the model will be highly correlated with judges' scores.

METHODS

1. Participants

Female athletes in middle school or higher who participated in the 2015 National Gymnastics Championship held in Gwangju, Korea (n = 22; age 18.64 ± 3.62 years; height 153.00 ± 6.45 cm; weight 44.73 ± 7.31 kg) were enrolled in this study. They were all capable of the Yurchenko layout with a 360° twist. Prior to the game, consent forms were obtained only from the coaches in order not to affect the athletes' performance. Consent forms and physical measurements of the athletes

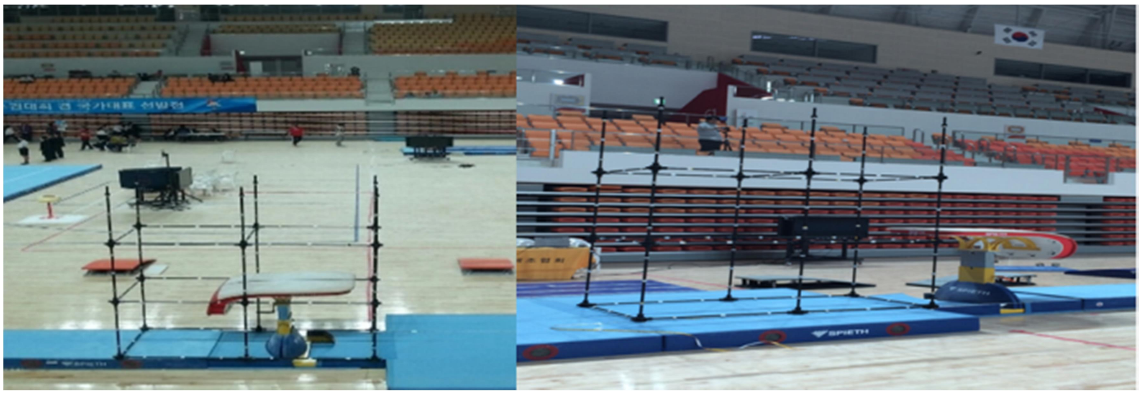

Figure 1. Overview of calibration frame set-up and calibration process before competitions (Park & Kim, 2016)

were taken after the game.

2. Measurements

Four video cameras (EX-F1, Casio, Japan) were installed in the audience section. The cameras collected data at a sampling rate of 60 Hz and shutter speed of 1/500 s. As shown in Figure 1, calibrations were performed for the entire vaulting space by moving the calibration frame in 2-m intervals from the round-off mat to the landing zone. To compute three-dimensional coordinates of the marker position, the direction of forward movement was defined as the +Y axis, right-side of the forward direction as the +X axis, and the vertical upward direction as the +Z axis. As the use of a light emitting diode (LED) was not allowed during the competition, the moment at which the athlete's hands first contact the mat in the round-off phase was set as the reference time frame for synchronizing the cameras. The space coordinates were computed via the direct linear transformation methods suggested by Abdel-Aziz and Karara (1971). Furthermore, as we could not attach reflective markers on the athletes, 15 landmarks (head, left and right shoulders, left and right elbows, left and right wrists, left and right ankles, and left and right tips of feet) were manually digitized on the recorded video in the Kwon3D XP (Visol, Korea) software (Park & Kim, 2016). Plagenhoef, Evans, and Abdelnour's (1983) body segment parameters were used, and noises in the digitized data were eliminated using a four-dimensional Butterworth low frequency pass filter (cutoff frequency 8 Hz). Some of the 22 athletes competed in both preliminary and final sessions, and 32 competition video clips in total were processed and statistically analyzed. The final score for each athlete was the average score of four judges, after excluding the highest and lowest scores from a total of six judges, and we recorded the score displayed on the score board. The scores were cross-checked by the posting on the Korea Gymnastics Association website.

3. Data processing

As shown in Figure 2, the phases for analysis were divided into round-off, board contact, pre-flight, horse contact, and post-flight. Events were divided into the moment at which the hands touch the floor following a round-off entry (floor touch down, E1), moment at which the hands are taken off the floor (floor take off, E2), moment at which the feet touch the board (board touch down, E3), moment at which the feet are taken off the board (board take off, E4), moment at which the hands touch the horse (horse touch down, E5), moment at which the hands are taken off the horse (horse take off, E6), moment at which the body reaches peak height during post-flight (peak height, E7), and the moment at which the feet contact the landing mat (landing, E8), respectively.

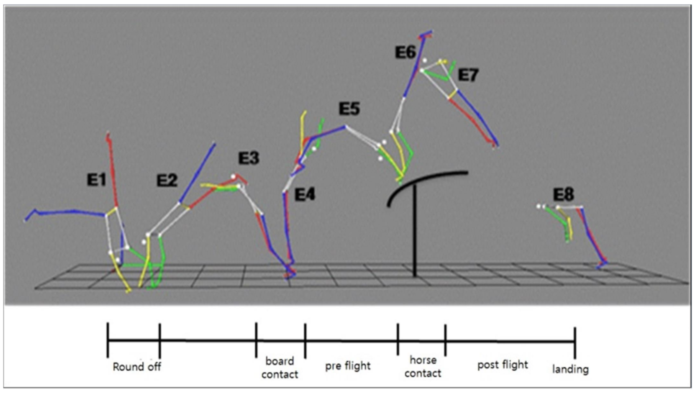

Figure 2. Definition of major events and phases during Yurchenko layout with 360˚ twist (Park & Kim, 2016)

Figure 3 shows the definitions of each kinematic variable. The entrance angles (θ_1, θ_5) and departure angles (θ_2, θ_6) of the round-off and horse contact phases were, respectively, defined as the absolute angle formed between the vector that connects the midpoint of both hands to the center of mass (CM) and the negative y-axis (leftward horizontal line). The entrance angle (θ_3) and departure angle (θ_4) of the board contact phase were, respectively, defined as the absolute angle formed between the vector that connects the midpoint of both feet to the CM and negative y-axis (leftward horizontal line). The joint angles of the upper and lower limbs were defined as the vector angles between the proximal and distal segments.

4. Development of modified deterministic model

Hay and Reid's (1988) deterministic model placed the goal (records

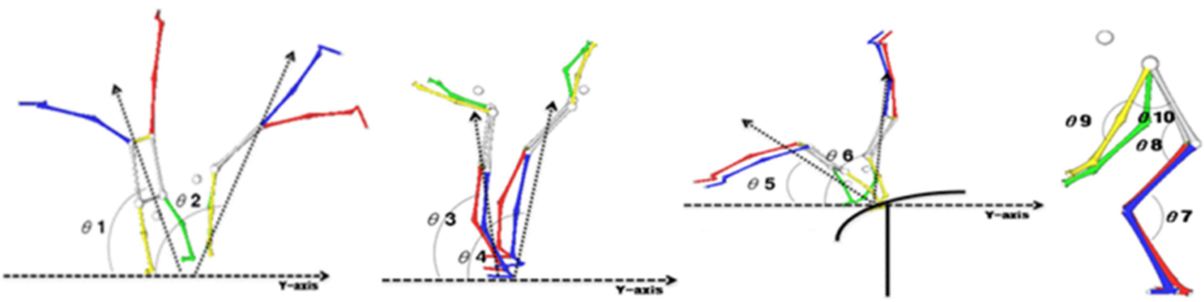

Figure 3. Definition of entrance angles, departure angles of round-off, board contact, and horse contact and joint angles of the upper and lower limbs (Park & Kim, 2016)

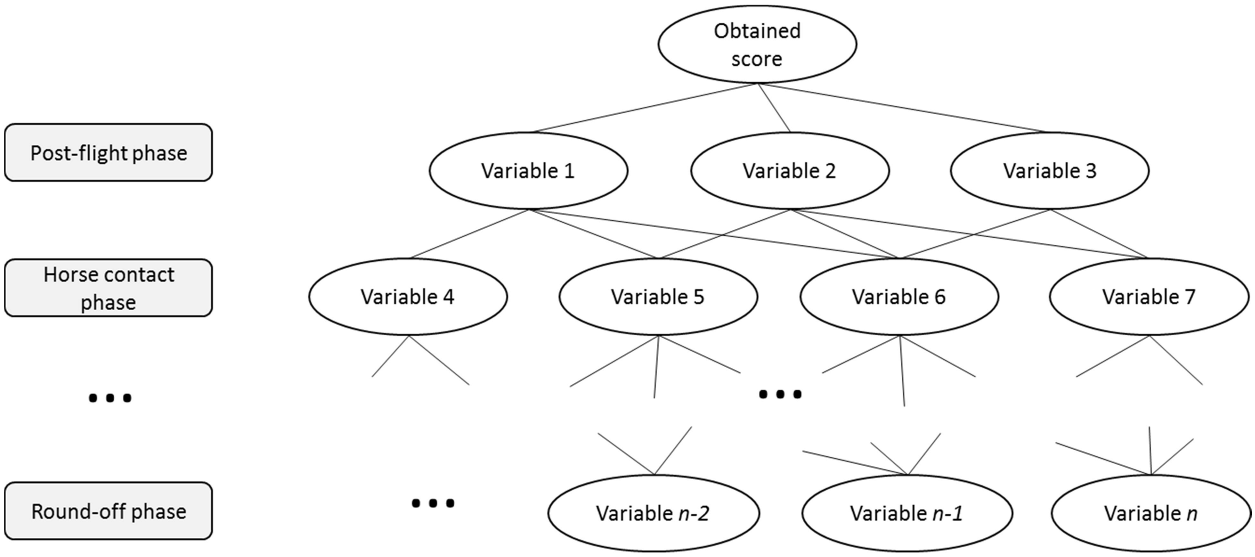

Figure 4. Modified deterministic model showing kinematic variables affecting the obtained point and correlative relationships between proceeded variables and current phase variables

or scores) at the top and linear and angular motion variables that influence the goal in the bottom to examine the cause and effect relationship between the goal and variables. This study partially modified Hay and Reid's (1988) deterministic model. They sometimes placed variables of different phases at the same levels from a causal perspective, but this study arranged the variables in time series. In other words, the obtained score was set as the goal, and the post-flight variables is placed immediately below the goal. Then, the post-flight variables were followed by horse contact variables, pre-flight variables, board contact variables, and round-off variables hierarchically. Subsequently, we analyzed the correlation between the kinematic variables in the current phase with those of the preceding phase to identify the effects of preceding phase variables on current phase motion (Figure 4).

5. Statistical analysis

All statistical analyses were performed using SPSS® 20.0 (IBM, Chicago, IL, USA) at a significance level of .05. The relations between the final score and phase-specific kinematic variables were examined with the Pearson product-moment correlation, and a hierarchical regression analysis was also performed to understand the variables' contributions to changes in the final score. In the hierarchical regression analysis, variables significantly associated with the final score were extracted in each phase and were sequentially added in the regression equation to examine the effectiveness of added variables from the introduction of each variable. Furthermore, correlations among the variables in preceding and current phases were examined to identify their kinematic relevance.

RESULTS

1. Effects of mechanical variables of each phase on the obtained points

Table 1 summarizes the correlations among the final score and phase-specific kinematic variables, while Table 2 summarizes the results of the simple regression analysis with only the significant variables. Performance score was significantly negatively correlated with the round-off phase time (r = -.352, p < .05) and board contact phase time (r = -.393, p < .05), indicating high scores were associated with shorter phase times. The remaining variables were not statistically associated with the final score. Simple regression analysis showed that the round-off phase time and board contact phase time accounted for 14.2% and 15.4% of score variations, respectively. Pre-flight kinematic variables were not significantly correlated with the final score. In the horse contact phase, phase time (r = -.565, p < .01), horizontal displacement of body (r = -.486, p < .01), horse takeoff angle (r = -.496, p < .01), and twist angular velocity (r = -.443, p < .05) had significant negative correlations with performance score, where a higher score was associated with shorter phase time, shorter horizontal displacement of body, smaller horse takeoff angle, and smaller twist angular velocity. Simple regression showed that phase time accounted for 32.0%, horizontal displacement of body accounted for 23.7%, horse takeoff angle accounted for 24.6%, and twist angular velocity accounted for 19.6% of score variations. In the post-flight phase, peak height (r = .587, p < .01), resultant linear velocity (r = .460, p < .01), and knee angle at landing (r = .516, p < .01) had significant positive correlations with performance score, where a higher score was associated with higher peak height, higher resultant velocity, and larger knee angle at landing. Simple regression showed that peak height, resultant linear velocity, and knee angle at landing each accounted for 34.4%, 21.1%, and 26.6%

Table 1. Descriptive statistics and Pearson correlations with judges' scores for kinematic variables of each phase

Variables	Mean ± *SD*	Min	Max	*r*
Round-off phase				
Phase time (sec)	0.30 ± 0.03	.23	.40	-.352*
Horizontal displacement of body CM (m)	1.61 ± 0.19	1.22	2.05	-.199
Vertical displacement of body CM (height %)	11 ± 3	4	19	-.325
Resultant linear velocity of body CM (m/s)	-1.22 ± 0.43	-2.48	-.40	.074
Round-off entrance angle (°)	69.74 ± 4.98	59.54	79.30	.215
Round-off takeoff angle (°)	108.58 ± 5.85	97.44	119.13	-.082
Board contact phase				
Phase time (sec)	0.13 ± 0.02	.10	.17	-.393*
Horizontal displacement of body CM (m)	0.57 ± 0.08	.41	.73	-.262
Vertical displacement of body CM (height %)	36 ± 5	28	47	-.225
Resultant linear velocity of body CM (m/s)	0.76 ± 0.40	-.62	2.01	.205
Hip angle (°)	-13.46 ± 10.37	-49.25	-.95	-.040
Knee angle (°)	17.91 ± 7.93	1.25	35.23	.174
Board entrance angle (°)	55.55 ± 6.27	39.32	67.88	.049
Board takeoff angle (°)	98.63 ± 4.22	91.40	105.82	-.148
Angular velocity of CM during board contact (°/s)	473.12 ± 92.44	319.12	755.90	-.007
Pre-flight phase				
Phase time (sec)	.12 ± .02	.10	.17	.081
Horizontal displacement of body CM (m)	.51 ± .08	.38	.68	.132
Vertical displacement of body CM (height %)	41 ± 6	28	56	.301
Resultant linear velocity of body CM (m/s)	-.79 ± .56	-.157	1.54	-.181
Horse contact phase				
Phase time (sec)	0.22 ± 0.02	.20	.27	-.565**
Horizontal displacement of body CM (m)	0.66 ± 0.07	.50	.82	-.486**
Vertical displacement of body CM (height %)	52 ± 5	40	67	-.010
Resultant linear velocity of body CM (m/s)	-1.23 ± 0.38	-2.17	-.54	.334
Horse entrance angle (°)	24.84 ± 7.89	11.75	41.22	.068
Horse takeoff angle (°)	89.05 ± 5.25	79.69	98.75	-.496**
Twist angular velocity (°/s)	72.82 ± 31.13	1.55	121.85	-.442*
Change of elbow flexion angle (°)	21.38 ± 14.28	.98	64.97	.005
Post-flight phase & landing				
Phase time (sec)	0.86 ± 0.05	.77	.97	.105
Horizontal displacement of body CM (m)	2.06 ± 0.22	1.68	2.45	.341
Resultant linear velocity of body CM (m/s)	3.33 ± 0.35	2.56	4.13	.460**
Vertical peak height (height %)	139 ± 5	131	151	.587**
Hip angle at landing (°)	108.32 ± 17.28	72.84	145.51	.169
Knee angle at landing (°)	106.13 ± 29.53	65.18	166.16	.516**

*p < .05, **p < .01, CM =center of mass, SD = standard deviation

Table 2. Simple linear regression analysis of kinematic variables on the obtained point

Independent variables	R^2	B	SE	β	*t*	*p*
Round-off phase						
Phase time	.142	-8.955	4.367	-.352	-2.060	.048*
Board contact phase						
Phase time	.154	-16.418	7.136	-.393	-2.301	.029*
Horse contact phase						
Phase time	.320	-19.247	5.125	-.565	-3.755	.001**
Horizontal Displacement of body CM	.237	-5.575	1.828	-.486	-3.049	.005**
Horse takeoff angle	.246	-.080	.026	-4.96	-3.132	.004**
Horse twist angular velocity	.196	7.302	.004	-.442	-2.702	.011*
Post-flight phase						
Vertical peak height	.344	8.430	2.124	.587	3.968	.001**
Resultant linear velocity of body CM	.211	1.098	.387	.460	2.835	.008**
Knee angle at landing	.266	.015	.005	.516	3.298	.033*

**p* < .05, ***p* < .01, B = unstandardized coefficient, β = standardized coefficient, SE = standard error

of score variations, respectively.

2. Effects of multiple kinematic variables on the obtained point

Table 3 is the results of a hierarchical regression analysis with kinematic variables significantly correlated with performance score. Kinematic variables from the round-off phase to post-flight phase were sequentially entered in the regression equation. Model 1 only considered phase time, which was the only round-off variable that showed significant correlation with performance score, and Model 2 included phase times in the round-off and board contact phases. Model 3 included signifi - cant variables in the horse contact phase in addition to Model 2 variables, and Model 4 included significant variables in the post-flight phase with Model 3 variables. The results revealed that phase times of the round-off and board contact phases in Model 2 only accounted for 29.1% of score variations. The explanatory power of Model 3 increased to 50.3%, with the addition of horse contact variables (phase time, horizontal displacement, horse takeoff angle, twist angular velocity). Model 4, with the addition of post-flight variables, accounted for 64.9% of score variations. Twist angular velocity in Model 3 and knee angle at landing in Model 4 were strongly correlated with performance score (p <. 05).

3. Relationships of precursor variables on the current kinematic variables

Figure 5 is an illustration of the relationships between kinematic variables of each phase with the final goal (performance score) and the relationships (correlation coefficient and coefficient of determination) between current kinematic variables with precursor variables in each phase from the round-off to the post-flight. Performance score was significantly affected by peak height (r = .587, R^2 = .34), resultant linear velocity (r = .460, R^2 = .21), and knee angle at landing (r = .516, R^2 = .26) of the post-flight phase (p < .05). Peak height in the post-flight phase was negatively affected by horse contact phase time (r = -.490, R^2 = .24), and resultant linear velocity in the post-flight phase was affected by phase time (r = -.672, R^2 = .45) and resultant linear velocity (r = .626, R^2 = .39) in the horse contact phase (p < .05). However, knee angle at landing in the post-flight phase was not affected by kinematic variables in the preceding phase. Horse contact phase time was significantly affected by pre-flight phase time (r = -.446, R^2 = .07), horizontal body displacement (r = -.405, R^2 = .16), and vertical body displacement (r = -.541, R^2 = .29) (p < .05), respectively. Pre-flight horizontal body displacement was affected by horizontal body displacement (r = -.375, R^2 = .14) and takeoff angle (r = -.429, R^2 = .20) in the board contact phase, while pre-flight vertical displacement of body was affected by phase time (r = -.497, R^2 = .24), horizontal body displacement (r = -.468, R^2 = .22), vertical body displacement (r = -.463, R^2 = .21), and takeoff angle (r = -.655, R^2 = .43) in the board contact phase (p < .05), respectively. Phase time (r = -.350, R^2 = .12) and horizontal body displacement (r = -.430, R^2 = .28) in the board contact phase were each negatively affected by round-off entrance angle (p < .05). Takeoff angle in the board contact phase was positively affected by round-off takeoff angle (r = .391, R^2 = .15) (p < .05).

Resultant linear velocity in the horse contact phase was negatively affected by pre-flight resultant velocity of body (r = -.568, R^2 = .29), which in turn was negatively affected by resultant linear velocity in the board contact phase (r = -.451, R^2 = .18) (p < .05). The resultant linear velocity in the board contact phase was negatively affected by resultant

Table 3. Hierarchical multiple regression analysis of the obtained point

Model		R^2	B	SE	β	*T*	*p*
1	Constant	.124	14.877	1.323		11.243	<.001**
	Phase time (round-off)		-8.995	4.367	-.352	-2.060	.048*
2	Constant	.291	17.568	1.589		11.056	<.001**
	Phase time (round-off)		-9.973	4.013	-.390	-2.485	.019*
	Phase time (board contact)		-17.35	6.636	-.411	-2.615	.014*
3	Constant	.503	18.095	2.532		7.146	<.001**
	Phase time (round-off)		1.122	5.254	.044	.214	.833
	Phase time (board contact)		-7.803	7.379	-.185	-1.058	.300
	Phase time (horse contact)		-15.73	7.878	-.462	-1.996	.057
	Horizontal displacement (horse contact)		1.571	2.986	.137	.526	.603
	Horse takeoff angle		-.020	.037	-.125	-.554	.585
	Horse twist angular velocity		-.012	.005	-.436	-2.181	.039*
4	Constant	.649	12.717	4.383		2.901	.008**
	Phase time (round-off)		2.552	4.913	.100	.519	.609
	Phase time (board contact)		-3.279	6.845	-.078	-.479	.637
	Phase time (horse contact)		-9.088	10.222	-.267	-.889	.384
	Horizontal displacement (horse contact)		1.479	3.106	.129	.476	.639
	Horse takeoff angle		-.048	.035	-.300	-1.389	.179
	Horse twist angular velocity		-.008	.005	-.303	-1.637	.116
	Vertical peak height		3.093	3.046	.215	1.015	.321
	Resultant velocity of body CM		-.053	.635	-.022	-.083	.934
	Knee angle at landing		.009	.004	.325	2.118	.046*

*$p<.05$, **$p<.01$, B = unstandardized coefficient, β = standardized coefficient, SE = standard error

linear velocity in the round-off phase (r = -.589, R^2 = .29) ($p<.05$).

DISCUSSION

Because vaults are completed within two seconds, judges must quickly assess and score the performance at each phase based on objective criteria. This study aimed at exploring the kinematic variables that affect judges' scores and their relationships to the scores. Relations between the variables and the final score were analyzed with correlation and regression analyses, and relations among the variables were examined based on the modified deterministic model suggested by Hay and Reid (1988).

The results revealed that phase times of the round-off and board contact phases—the early phases of a vault—significantly affect judges' scores. These two variables had negative relations with the score, and together, they accounted for 29.1% of score variations. This finding was in line with the report by Yoon and Min (2011) where a shorter board contact time was associated with a higher performance score, suggesting that board contact should be shortened for a good score. Phase time was crucial because fast horizontal velocity in the board contact phase translates to a fast vertical velocity during horse contact phase (Yeo, 2006a; Yoon & Kim, 2006a; Yoon et al., 2008). Contrary to our prediction, none of the kinematic variables in the pre-flight phase had significant effects on the final score. Previous studies have reported that shorter pre-flight phase time, and hence shorter distance, increase the chance of a successful performance or lead to high scores, but the same was not observed in the present study (Song et al., 2015; Yeo, 2006b; Yoon et al., 2008; Yoon & Min, 2011).

The effects of the kinematic variables in the horse contact and post-flight phases had on the final score were very similar with those reported previously. Phase time, horizontal displacement of the body, horse takeoff angle, and twist angular velocity of the horse contact phase, respectively, had negative correlations with the final score. In other words, the score was higher the shorter the horse contact phase

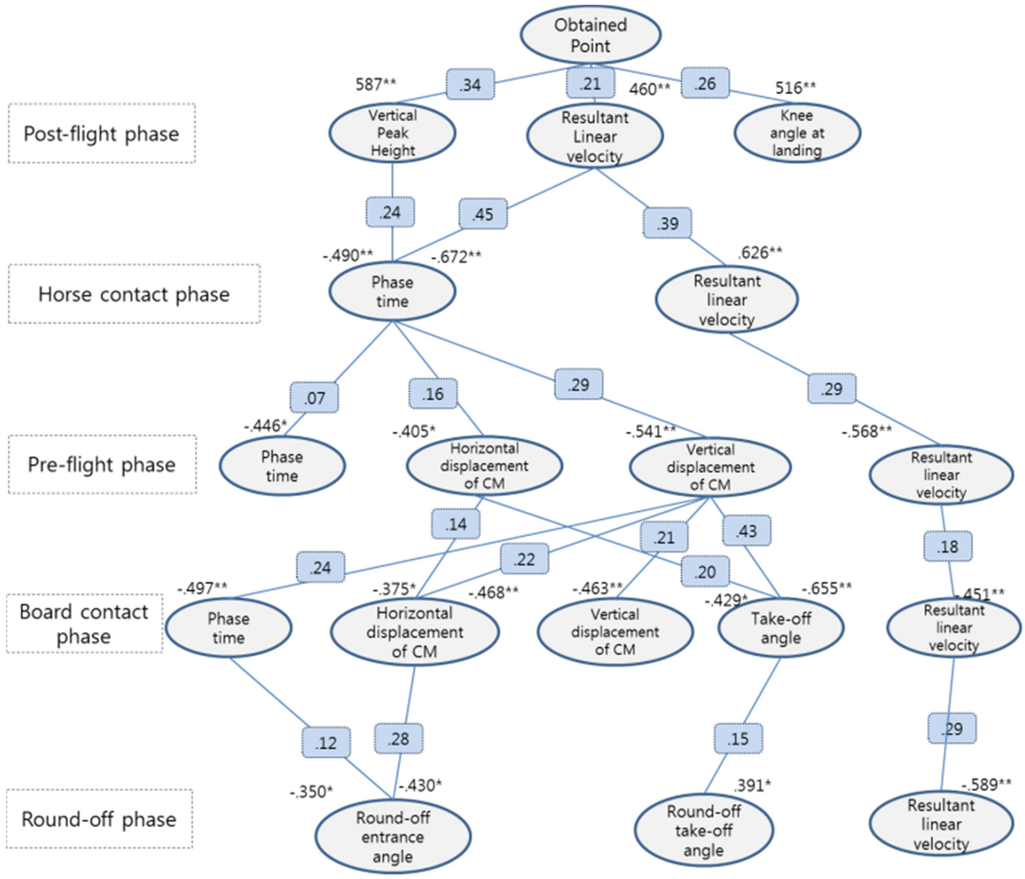

Figure 5. Modified deterministic model for Yurchenko layout with 360° twist in female vaults. Model shows kinematic variables of post-flight phase that determines the obtained point and correlative relationships between proceeded and current kinematic variables.

and the less the body was displaced to the direction of movement (Park & Kim, 2016; Song et al., 2015; Yeo, 2006a, 2006b; Yoon & Kim, 2006a, 2006b). This is possible when the horizontal kinetic energy onto the horse is converted to vertical kinetic energy, highlighting the importance of blocking with strong shoulders. Weak blocking leads to longer translation, resulting in larger horse takeoff angle. Therefore, an inefficient conversion of horizontal velocity into vertical velocity had negative effects on post-flight vaulting (Park & Kim, 2016; Song et al., 2015; Yeo, 2006a, 2006b; Yoon & Kim, 2006a, 2006b).

Kwon et al. (1990), who studied the 360° twisting layout, reported that high scorers had smaller horse twisting angular velocity than low scorers, which supports our findings. Song et al. (2015) also suggested that trunk rotation (sagittal plane) must be adequately performed than twisting (transverse plane) for a better vaulting performance. They argued that the timing of increasing the rotational velocity is important; the stronger the trunk twisting rotation, the weaker the vertical force and the lower the score, indicating that reducing twisting angular velocity at horse takeoff would result in a higher score (Kwon et al., 1990). The multiple regression model including kinematic variables up to the horse contact phase accounted for 50.3% of the score variation. Adding to the regression model, the peak height, resultant linear velocity, and knee angle at landing in the post-flight phase, which had all positive effects on performance score, increased the explanatory power to 64.9%. In general, high scorers displayed high peak height, which enabled a more comfortable landing, leading to higher knee angles. Although this postural component was not significantly related to preceding kinematic variables, it was partially in line with previous studies reporting that judges place the greatest emphasis on landing posture in scoring (Takei, Blucker, Dunn, Myers, & Fortney, 1996).

The most influential variable on the final score was post-flight peak height (r = -.587), followed by horse contact time (r = -.565), knee angle at landing (r = -.516), and horse takeoff angle (r = -.587). These were similar to previous arguments that horse contact and post-flight phases are the determinants of judges' scores (Park & Kim, 2016; Song et al., 2015; Yeo, 2006a, 2006b; Yoon & Kim, 2006a, 2006b). One reason behind the strong effects of post-flight variables on the score may be related to the location of judges' tables in Korea. The Korea Gymnastics Association specifies score deduction criteria for each phase. However, judges are positioned primarily in the landing area and not throughout each of the phase areas in competitions held in Korea, naturally elevating the relative importance of horse contact and landing postures in the judges' assessment. Accordingly, we speculate that rearranging the judges' locations in national competitions or having the vault on an elevated podium would offer judges a more effective view of the vaulting and subsequently improve the scoring process. Furthermore, because of the fact that many current coaches also serve as judges in national-level competitions, subjectivity could not be completely eliminated (Han, Lee, Yoon, & Park, 2011). Additional studies are required to explore a more objective scoring system.

Hay and Reid (1988) argued that mistakes in vaulting are results of mistakes in preceding phases. In other words, landing flaws are caused by improper post-flight techniques, post-flight errors by improper horse contact techniques, horse contact mistakes by improper pre-flight techniques, and pre-flight flaws by improper board contact techniques. Therefore, we applied a deterministic model upon the assumption that a good understanding of the kinematic variables in the preceding phases would lead to a better understanding of the kinematic of the current phase.

Three kinematic variables (i.e. peak height, resultant linear velocity, and knee angle at landing) in the post-flight phase were most highly correlated with the final score. We then sequentially examined the preceding variable that affects these three variables and found that knee angle, unlike the other two variables, was not affected by any other precursors. This means that judges scored landing technique independently of other variables. Although it was not a study on the Yurchenko vaults, Takei et al. (1996) found a high negative relation between the deduction components for landing in a vault and the final score, and Takei (2007) stressed the importance of landing with the finding that deductions in landing accounted for 85% of variance in the final score.

The resultant linear velocity in the round-off phase has significant effects on the resultant linear velocities in succeeding phases. Furthermore, the entry and takeoff angles during round-off significantly affected the subsequent board contact phase time, horizontal displacement, and board takeoff angle, respectively. In addition, together with the vertical displacement of body in the board contact phase, they all affected vertical displacement and horizontal displacement in the preflight phase. These eventually affected phase time and resultant linear velocity in the horse contact phase, subsequently affecting the post-flight phase. Thus, even though round-off entry angle and resultant linear velocity did not directly affect the final score, they partially contributed to the final score by affecting the kinematic variables in the succeeding phases. We speculate this to be partially attributable to the distinguishing features of the Yurchenko vault. In a Yurchenko vault, the athlete enters the springboard with a side rotation of the body, so the technique incorporates both the angular motion components (round-off entry angle) and linear motion components (resultant linear velocity of the CM). Moreover, the athlete must maintain an adequate running speed and touch the floor at a desirable distance in the round-off phase to effectively convert the horizontal energy into rotational energy. Although not specifically addressing a round-off, Takei (2007) showed that inaccurate steps immediately before the board contact phase not only impacts this phase but also subsequent phases, stressing the importance of the round-off phase in which the linear motion is transformed to rotational motion.

This study had a few limitations. First, reflection markers could not be used due to the limitations of the competition environment, and manual digitizing of the major landmarks could have undermined the accuracy of the coordinates. Second, the image sampling rate (60 Hz) was relatively low, and the disuse of a sync LED may have increased the risk of error in time synchronization.

CONCLUSION

Post-flight peak height had the greatest effect on the final score of a vault, followed by horse contact time, knee angle at landing, and horse takeoff angle, respectively. A strong horse blocking with a strong shoulder led to shorter horse contact and smaller horse takeoff angle. This enabled the athlete to jump higher in the post-flight phase, thus subsequently giving the athlete more time for landing. The deterministic model revealed that round-off entry and takeoff angles affected phase time, displacement, and posture in subsequent phases. The resultant linear velocity of the round-off phase affected the resultant linear velocities in the ensuing phases. Knee angle at landing was not affected by any of the precursors and was independently assessed by the judges. In conclusion, performance scores were mainly affected by kinematic variables in the post-flight and horse contact phases, which were in turn directly and indirectly affected by kinematic variables in preceding phases.

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