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Comprehensive Kinematic Analysis of Novel Artistic Gymnastic Technique: A Case Study of Yeo Seojeong Vault

Jooho Song[a] and Don Hyung Lee[b*]

[a]*Department of Physical Education, Chungbuk National University, Cheongju, Korea*
[b]*Department of Health Policy Research and Evaluation, Korea Health Promotion Institute, Seoul, Korea*

Abstract

The purpose of this study was to explore key kinematic variables of Yeo Seojeong vault by analysing series of vaults performed by Yeo Seo Jeong (YSJ) in order to provide technical support for YSJ and coaches to develop successful training strategy as well as promote adoption of the technique among gymnasts. Two-dimensional video recordings of YSJ during 2019 Korea Cup (1 successful vault) and practice session (3 unsuccessful vaults) were taken. Phase time, changes in position of body centre of mass, velocity of body centre of mass, and changes in various joint angles, and changes in angular velocity were subjected to kinematic analysis. Kinematic analysis revealed that successful vault was possible when YSJ had fast horizontal velocity at horse touch down as well as fast trunk rotation during horse contact, these allowed her to have faster thigh rotation and take-off angle exceeding 90 degrees at horse take-off resulting to reach maximum height and the length during post-flight. Together with higher and longer post-flight, faster rotation and twisting warranted the successful completion of Yeo Seojeong vault. From the unsuccessful vaults, we found that slow horizontal velocity and bent body posture at board contact as well as low body COM, small horizontal displacement of body COM, and slow vertical velocity at every preparation phase had adverse effect on the horse take-off, i.e. improper blocking, weak propulsion. These resulted rather insufficient post-flight with deceleration of rotation and twisting in descending phase of post-flight leading to insecure landing.

Key words: biomechanics, gymnastics, kinematic, olympics, vaults, Yeo Seo Jeong

Introduction

Ever since the winning two gold medals from Seoul Asian Games in 1986, unlike its male counterpart, international performance of Korean female artistic gymnastic has been stagnated for more than 30 years. However, talented young female gymnast Yeo Seojeong (YSJ) won a gold medal in the vault event from Jakarta Palembang Asian Games in 2018, which made her to be one of the major contender for a medal in 2020 Tokyo Olympics. Competing in her first adults competition at 2018 World Championships, YSJ scored average score of 14.233, which had put her 5th out of 8 finalists. This was rather disappointing; however, she has shown that she is not far from the winning the medal. Indeed, YSJ showed her potential by winning a gold medal from 2019 Korea Cup with introduction of new vault technique. This new technique is a variation of Yang Hak Seon vault (Federation of International Gymnastics, 2020), involving handspring forward and a salto forward with a 720-degree twist. International Gymnastics Federation (FIG) has

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Correspondence : donlee@khepi.or.kr

officially authorized this new technique with difficulty score of 6.2 and named this as YEO Seojeong (Federation of International Gymnastics, 2020). Therefore, expectation for the medal from the Olympics is higher than ever before.

Other contenders for a medals are world class gymnasts such as Simone Biles, Shallon Olsen, and Alexa Moreno, who won medals from the event YSJ competed in 2018 (World Championships). In 2018, these gymnasts performed more difficult technique than YSJ, therefore in order for YSJ to win the medal, she needs to execute Yeo Seojeong vault perfectly since it has the second highest difficulty score (6.2) after the Biles with difficulty score of 6.4. Thus, providing technical support, which would aid her to perform successful Yeo Seojeong vault consistently, might be pivotal to secure a medal at the Olympics. However, currently we do not have much knowledge on this novel technique since we have only observed the performance at the 2019 Korea Cup. In order to enhance our knowledge regarding Yeo Seojeong vault, biomechanical analysis, especially comprehensive kinematic analysis, is a good option. Therefore, the purpose of this study was to explore key kinematic variables of Yeo Seojeong vault by analysing series of vaults performed by YSJ in order to provide technical support for YSJ and coaches to develop successful training strategy. This study also aimed to provide comprehensive understanding of kinematic variables associated with YEO Seojeong vault, facilitating its adoption by other gymnasts striving to achieve high scores in competition. Since Yeo Seojeong vault can only be performed by YSJ and considering its level of difficulty, our best option for the data were successful trial collected during Korea Cup 2019 and unsuccessful trials collected from the practices.

Methods

Subject

The subject was YSJ, a 16 years old female gymnast with 7 years of experience. YSJ's height and weight were 150 cm and 46 kg. Two-dimensional video recordings of YSJ during 2019 Korea Cup and practice session were taken. Ethical approval was obtained from the Institutional review board of Korea Institution of Sport Science (approval number : KISS-2004-2010-01). This study was sanctioned by Korean Gymnastics Association.

Data collection

Five Sony (JPN) NEX-FS700 digital video cameras were used for video recordings. Video recordings were done at 60 frames per second (120 Hz) with Full HD quality (1920 × 1080). Figure 1 shows the layout of

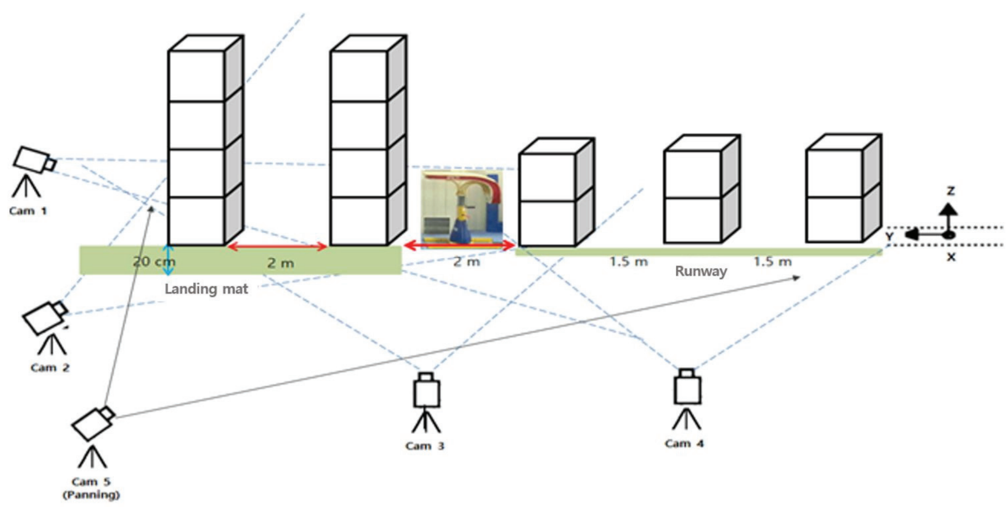

Figure 1. *Layout of cameras and control point installation*

video cameras setting as well as Visol's control points (1 cube = 1 x 1 x 1 meters) for creation of global coordinate system, which was identical to setting used by Song et al. (2018). Five video cameras filmed two control points at 120 Hz with shutter speed of 1/500 s and then 3D coordinates were set using direct linear transformation method (DLT, Abdel-Aziz & Karara, 1971) by merging five video recordings obtained from video cameras.

Data Processing

KWON3D XP 4.0 (Kwon, 2011) was used to process video recordings and YSJ’ s 3D coordinates were obtained from calculation of real space coordinates using control point. X-axis was defined as line perpendicular to the forward running direction, y-axis was defined as the line parallel to the forward running direction, and z-axis was defined as the vertical line perpendicular to the horizontal surface while human body model was defined as rigid system, which is articulated by 16 body segments consisting of 21 joints. Two-dimensional coordinates obtained from each camera were synchronized by using third spline function interpolation and DLT method was used to calculate 3D coordinates. The errors caused by digitising were smoothed using a digital filter (low-pass Butterworth, second order, cut-off frequency = 10 Hz).

Data analysis

Data of one successful vault and three unsuccessful vaults were collected and analysed. Unsuccessful vaults were determined by agreement between coach and research team, while successful vault was the one that YSJ performed during 2019 Korea Cup. Successful vault was named S1, while unsuccessful vaults with landing on the mat and backward step to collapse, landing and sitting down, and collapse with side turn were named F1, F2 and F3, respectively. In order to explore the kinematics of Yeo Seojeong vault, key events and phases were established as shown in Figure 2, based on the previous study by Song et al. (2018). Below are the definition of each events and phases.

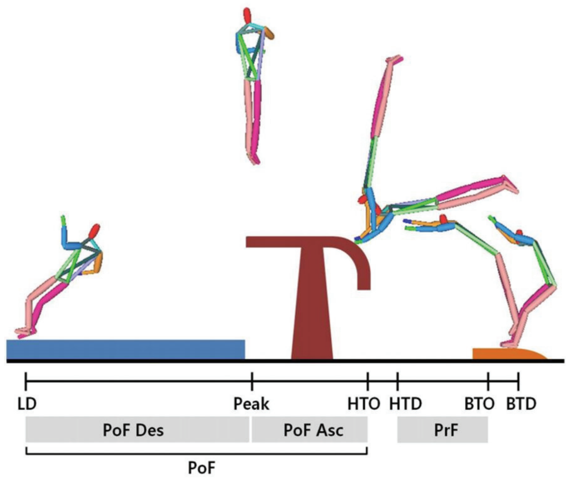

Figure 2. *Events and phases of the Yeo Seojeong vault*

Events;

BTD (Board touchdown): the point when the feet touch down on the board

BTO (Board take-off): the point of take-off from the board

HTD (Horse touchdown): the point when the hands touch down on the horse

HTO (Horse take-off): the point of take-off from the horse

Peak: the highest point the CoM reaches during the in-flight move in the post-flight stage

LD (Landing): the point when the feet touch down on the mat

Phases;

BC (Board contact): board contact phase, when the feet touch the board

PrF (Pre-flight): pre-flight phase, from the moment of take-off from the board to the moment left hand touches the horse

HC (Horse contact): horse contact phase, when both hands touch the horse

PoF (Post-flight): post-flight phase, from the moment the right hand takes-off from the horse to the moment the feet touch down on the mat

Based on the previous studies, key kinematic variables for vault were subject to analysis (Song &

Park, 2016; Takeiet al., 1996, Takei, 2007). These variables were phase time, changes of body Centre of Mass (COM) according to phase, changes in the angles of body segments, and changes according to body rotation, and changes in angular velocity. Figure 3 illustrates the definition of the angles; (1) hip joint angle, (2) knee joint angle, (3) shoulder joint angle, (4) Board touchdown and take-off angles, (5) Horse touchdown and take-off angles, (6) Thigh rotation angle, (7) Trunk rotation angle, and (8) Trunk twist angle.

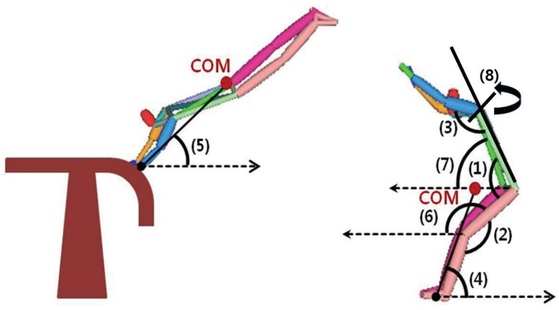

Figure 3. *Definition of angles*

Results

Phase time

Table 1 shows time taken for each phase during Yeo Seojeong vault. The vaulting time for S1 was 1.32 s, while F1, F2, F3 were 1.28 s, 1.32 s, 1.34 s, respectively. F1 had the shortest BC time at 0.1 s, while others had 0.12 s. However, F1 had the longest PrF time at 0.15 s, while others had 0.13s. For HC time, F1 had the shortest at 0.15 s, while others had 0.17 s. F1 also had the shortest PoF time at 0.88 s, and F3 had the longest at 0.92 s.

Change in position of body centre of mass

Table 2 shows vertical and horizontal displacement of body centre of mass (COM) during Yeo Seojeong vault. Horizontal displacement of body COM for S1 during Prf was relatively shorter at 0.65 m, however, S1 had largest horizontal displacement of body COM at 2.91 m during PoF. During BTO, HTD, and HTO,

Table 1. *Time taken for vault phases* (unit: s)

	BC	PrF	HC	PoF	Vaulting time
S1	0.12	0.13	0.17	0.90	1.32
F1	0.10	0.15	0.15	0.88	1.28
F2	0.12	0.13	0.17	0.90	1.32
F3	0.12	0.13	0.17	0.92	1.34

Table 2. *Horizontal and vertical displacement of body COM* (unit: m)

		BTD	BTO	HTD	HTO	Peak	LD	Displacement	
								PrF	PoF
Horizontal position of COM	S1	0.00	0.66	1.31	1.89	2.72	4.80	0.65	2.91
	F1	0.00	0.54	1.25	1.75	2.51	4.3	0.71	2.55
	F2	0.00	0.64	1.27	1.83	2.70	4.46	0.64	2.63
	F3	0.00	0.70	1.39	1.94	2.74	4.54	0.69	2.6
Vertical position of COM	S1	0.89	1.11	1.57	2.05	2.62	0.95		
	F1	0.86	1.06	1.56	1.99	2.49	0.8		
	F2	0.87	1.11	1.55	2.03	2.56	0.57		
	F3	0.88	1.08	1.51	2.00	2.59	0.83		

horizontal position of body COM for S1 were 0.66 m, 1.31 m, and 1.89 m, respectively. Horizontal displacement of body COM for F1 during Prf was the largest at 0.71 m, however, F1 had the smallest horizontal displacement of body COM at 2.55 m during PoF. During BTO, HTD, and HTO, horizontal position of body COM for F1 were relatively shorter at 0.54 m, 1.25 m, and 1.75 m, respectively. Horizontal displacement of body COM for F2 during Prf was the shortest at 0.63 m and had 2.63 m during PoF. During BTO, HTD, and HTO, horizontal position of body COM for F2 were 0.64 m, 1.27 m, and 1.83 m, respectively. Horizontal displacement of body COM for F3 during Prf was the larger than S1 at 0.69 m, however, it was shorter than S1 during PoF at 2.6 m. During BTO, HTD, and HTO, horizontal position of body COM for F1 were relatively longer at 0.70 m, 1.39 m, and 1.94 m, respectively.

Vertical position of body COM for S1 during Peak and LD were the highest at 2.62 m and 0.95 m, respectively, while it was relatively higher during BTD, BTO, HTD, and HTO at 0.89 m, 1.11 m, 1.57 m, and 2.05 m, respectively. Vertical position of body COM for F1 during Peak was the lowest at 2.49m. F1 had relatively lower vertical position during BTD, BTO, HTD, HTO, and LD at 0.86 m, 1.06 m, 1.56 m, 1.99 m, and 0.8 m, respectively. Vertical position of body COM for F2 during Peak was lower than S1 at 2.02 m, while during LD was the lowest at 0.57 m. F2 had similar vertical position of body COM compared to S1 during BTD, BTO, HTD, and HTO at 0.87 m, 1.11 m, 1.55 m, and 2.03 m, respectively. Vertical position of body COM for F3 during Peak was lower than S1 at 2.59 m, however, it was relatively higher during LD compared to other unsuccessful trials at 0.83 m. F3 had relatively lower vertical position of body COM during BTD, BTO, HTD, and HTO at 0.88 m, 1.08 m, 1.51 m, and 2.00 m, respectively.

Velocity of body centre of mass

Table 3 and 4 shows horizontal and vertical velocities of body COM during Yeo Seojeong vault. S1 had the fastest mean horizontal velocity during PoF at 3.22 m/s as well as HTD at 5.06 m/s. S1 was also relatively faster during BTD and BTO, 7.16 m/s and 4.77 m/s, respectively. Mean horizontal velocity for S1 during HTO was 2.31 m/s. Mean horizontal velocity for F1 during PoF was slower than S1 at 2.89 m/s. F1 had the slowest mean horizontal velocity during BTD at 6.5 m/s, however, had similar mean horizontal velocity compared to S1 during BTO at 4.64 m/s. Mean

Table 3. *Horizontal velocity of body COM* (unit: m/s)

	BC			HC			PoF Mean
	BTD	BTO	⊿V	HTD	HTO	⊿V	
S1	7.16	4.7	-2.46	5.06	2.31	-2.75	3.22
F1	6.5	4.64	-1.86	4.66	2.35	-2.31	2.89
F2	6.83	4.62	-2.21	4.67	2.44	-2.23	2.92
F3	7.34	5.24	-2.1	4.95	2.16	-2.79	2.84

Table 4. *Vertical velocity of body COM* (unit: m/s)

	BTD	BTO	HTD	HTO	LD	PoF Descend Mean
S1	-1.02	3.6	2.96	2.98	-4.58	-2.55
F1	-0.2	3.45	2.71	2.87	-4.72	-2.94
F2	-0.19	3.48	2.8	2.86	-4.71	-2.88
F3	-0.78	3.47	2.8	3.18	-4.82	-2.69

horizontal velocities for F1 during HTD and HTO were 4.66 m/s and 2.35 m/s, respectively. Mean horizontal velocity for F2 during PoF was slower than S1 at 2.92 m/s and during BTD, BTO, and HTD were also slower than S1 at 6.83 m/s, 4.62 m/s, and 4.67 m/s, respectively. Mean horizontal velocity for F2 during HTD was 2.44 m/s. Mean horizontal velocity for F3 during PoF was the slowest at 2.84 m/s, while F3 was the fastest during BTD and BTO at 7.34 m/s and 5.24 m/s, respectively. Mean horizontal velocity for F3 during HTD and HTO were 4.95 m/s and 2.16 m/s, respectively.

In terms of vertical velocities of body COM, S1 was the slowest during PoF descend at 2.55 m/s. However, S1 was the fastest during BTO and HTD at 3.6 m/s and 2.96 m/s, respectively. S1 was also relatively faster during HTO, at 2.98 m/s. F1 was the fastest during PoF descend at 2.94m/s, however, F3 was slower than S1 during BTO, HTD, and HTO at 3.45 m/s, 2.71 m/s, and 2.87 m/s, respectively. F3 was faster than S1 during PoF descend and HTO at 2.69 m/s and 3.18 m/s, however, F3 was slower than S1 during BTO at 3.47 m/s.

Change in angles

The angles we have analysed in this study were angle of major joints (hip, knee, shoulder, and neck), touchdown and take-off angles of the board and landing angles, rotation angle of thigh and trunk, and twist angle of the trunk,

Change in angle of major joints

Table 5 shows changes in joint angles during Yeo Seojeong vault. Hip joint angle for S1 during BTD was the smallest at 105 degrees, while F3 had the biggest hip angle at 109 degrees. However, hip angle for S1 during BTO was the biggest at 161 degrees, while F1 had the smallest hip angle at 148 degrees. Hip angle for S1 during HTD was 200 degrees and F1 had the biggest hip angle at 208 degrees, while F2 had the smallest hip angle at 194 degrees. Hip joint angle for S1 during HTO was 203 degrees and F1, F2 had the biggest hip angle at 206 degrees, while F2 had the smallest hip angle at 159 degrees. Hip angle for S1 during Peak was 159 degrees and F2 had the biggest hip angle at 169 degrees, while F3 had the smallest hip angle at 148 degrees. YSJ landed almost vertical to the ground for all trials, ranging 175 degrees~182 degrees, except for F2 at 170 degrees.

Knee angle for S1 during BTD was the greatest at 144 degrees, while F2 had the smallest knee angle at 125 degrees. Knee angle for S1 during BTO was the biggest at 174 degrees, while F3 had the smallest knee angle at 164 degrees. Knee angle for S1 during HTD was the biggest at 173 degrees, while F3 had the smallest knee angle at 147 degrees. Knee angle for S1 during HTO was the biggest at 175 degrees, while both F2 and F3 had the smallest knee angle at 158 degrees. Knee angle for S1 during Peak was 163 degrees and F1 had the biggest knee angle at 164 degrees, while F3 had the smallest knee angle at 156 degrees. Knee angle for S1 during LD was 155 degrees and F1 had the biggest knee angle at 157 degrees, while F2 had the smallest knee angle at 118 degrees.

Shoulder angles for S1 during BTO were relatively bigger at 125 degrees (left) and 120 degrees (right), while F2 had relatively smaller shoulder angles at 121 degrees (left) and 116 degrees (right). Shoulder angles for S1 during HTD and HTO were relatively bigger at 148 degrees (left) and 122 degrees (right) and 164 degrees (left) and 147 degrees (right), respectively. Shoulder angles for S1 during Peak were relatively bigger at 45 degrees (left) and 38 degrees (right).

Change in angles of board and horse touchdown and take-off and landing

Table 6 shows changes in angles of board and horse touchdown and take-off and landing for Yeo Seojeong vault. Board touchdown angle for S1 during BTD was 67 degrees, while F1 had the biggest angle at 71 degrees and F3 had the smallest angle at 66 degrees. Board take-off angle for S1 during BTO was 119 degrees, while F2 had the biggest angle at 120 degrees and F1 had the smallest angle at 114 degrees.

Table 5. *Change in the angle of major joints* (unit: degrees)

			BTD	BTO	HTD	HTO	Peak	LD
Hip joint angle	S1	L	105	161	200	203	159	182
	F1	L	107	148	208	206	150	180
	F2	L	106	150	194	191	169	170
	F3	L	109	158	198	206	148	175
Knee joint angle	S1	L	144	174	173	175	163	155
	F1	L	133	166	164	170	164	157
	F2	L	125	166	158	158	161	118
	F3	L	140	164	147	158	156	140
Shoulder joint angle	S1	L	158	125	148	164	45	50
		R	148	120	122	147	38	39
	F1	L	152	130	143	155	32	36
		R	153	118	126	154	34	40
	F2	L	147	121	128	166	37	44
		R	139	116	128	158	16	33
	F3	L	149	121	137	160	37	62
		R	147	121	130	143	20	49
Neck joint angle	S1		177	162	127	130	148	166
	F1		175	160	131	115	136	144
	F2		173	151	126	103	150	162
	F3		167	164	139	118	159	177

Table 6. *Board touchdown and take-off angle, horse touchdown and take-off angle, and landing angle* (unit: degrees)

	Board touchdown and take-off angle		Horse touchdown and take-off angle		Landing angle
	BTD	BTO	HTD	HTO	LD
S1	67	119	34	95	50
F1	71	114	36	95	38
F2	70	120	36	95	44
F3	66	117	30	96	48

Horse touchdown angle for S1 during HTD was 34 degrees, while F1 and F2 had the biggest angles at 36 degrees and F3 had the smallest angle at 30 degrees. Horse take-off angle for S1 during HTO was 95 degrees, which was similar to F1, F2, and F3. Landing angle for S1 was the biggest at 50 degrees, while F1 had the smallest angle at 38 degrees.

Change in angle of thigh rotation

Table 7 shows change in angle of thigh rotation (left side) during Yeo Seojeong vault. Thigh rotation angle for S1 during BTD was 40 degrees, while F3 had the biggest thigh rotation angle at 43 degrees. Thigh rotation angle for S1 during BTO was the biggest at 117 degrees, while F1 had the smallest thigh rotation angle at 103 degrees. Thigh rotation angle for S1 during HTD was 208 degrees and F1 had the biggest thigh rotation angle at 214 degrees, while F3 had the smallest thigh rotation angle at 200 degrees. Thigh rotation angle for S1 during HTO was the biggest at 300 degrees, while F2 had the smallest thigh rotation angle at 204

Table 7. *Thigh and trunk rotation, and trunk twist angle* (unit: degrees)

		BTD	BTO	HTD	HTO	Peak	LD
Thigh rotation	S1	40	117	208	300	396	768(48)
	F1	40	103	214	300	385	757(37)
	F2	39	113	204	294	405	753(33)
	F3	43	114	200	297	393	763(43)
Trunk rotation	S1	115	136	190	274(94)	421(61)	763(43)
	F1	114	135	187	269(89)	419(59)	752(32)
	F2	112	143	191	280(100)	436(76)	778(58)
	F3	113	134	181	265(85)	430(70)	761(41)
Trunk twist	S1	-3	5	-11	-27	11	681(-39)
	F1	-4	-6	-9	-30	8	650(-70)
	F2	-9	-7	-5	-24	38	668(-52)
	F3	-13	-8	-8	-28	15	680(-40)

degrees. Thigh rotation for S1 during Peak was 396 degrees and F2 had the biggest thigh rotation angle at 405 degrees, while F1 had the smallest thigh rotation angle at 385 degrees. Thigh rotation angle for S1 during LD was the biggest at 768 degrees, while F2 had the smallest thigh rotation angle at 753 degrees.

Change in angle of trunk rotation

Table 7 shows change in angle of trunk rotation during Yeo Seojeong vault. Trunk rotation angle for S1 during BTD was 115 degrees, which was similar to all other trials. Trunk rotation angle for S1 during BTO was 136 degrees, which was similar to all other trials. Trunk rotation angle for S1 during HTD was 190 degrees and F2 had the biggest trunk rotation angle at 191 degrees, while F3 had the smallest trunk rotation angle at 181 degrees. Trunk rotation angle for S1 during HTO was 274 degrees and F2 had the biggest trunk rotation angle at 280 degrees, while F3 had the smallest trunk rotation angle at 265 degrees. Trunk rotation angle for S1 during Peak was 421 degrees and F2 had the biggest trunk rotation angle at 436 degrees, while F1 had the smallest trunk rotation angle at 419 degrees. Trunk rotation angle for S1 during LD was 763 degrees and F2 had the biggest trunk rotation angle at 778 degrees, while F1 had the smallest trunk rotation angle at 752 degrees.

Change in angle of trunk twist

Table 7 shows change in angle of trunk twist during Yeo Seojeong vault. Trunk twist angle for S1 during HTD was -11 degrees and F1, F2, and F3 had the similar trunk twist angle to S1 ranging from -5 degrees to -9 degrees. Trunk twist angle for S1 during HTO was -27 degrees and F1 had the biggest trunk twist angle at -30 degrees, while F2 had the smallest twist angle at -24 degrees. Trunk twist angle for S1 during Peak was 11 degrees and F2 had the biggest trunk twist angle at 38 degrees, while F1 had the smallest twist angle at 8 degrees. Trunk twist angle for S1 during LD was the biggest at 681 degrees, while F1 had the smallest twist angle at 650 degrees.

Change in angular velocity

Change in angular velocity of thigh rotation

Table 8 shows change in angular velocity of thigh rotation during Yeo Seojeong vault. Angular velocity of thigh rotation for S1 during PrF was 687 deg/s and F1 had the fastest average angular velocity of thigh rotation at 739 deg/s, while F3 was the slowest at 643 deg/s. Angular velocity of thigh rotation for S1 during HC was 542 deg/s and F3 had the fastest average angular velocity of thigh rotation at 572 deg/s, while

Table 8. Angular velocities of the thigh and trunk (unit: degrees/s)

		BTO	HTD	HTO	Peak	LD	BC	PrF	HC	PoF	PoF Asc	PoF Des
Thigh rotation	S1	672	671	278	-	371	-	687	542	-	387	571
	F1	812	622	277	-	460	-	739	556	-	352	586
	F2	700	651	212	-	135	-	686	530	-	397	559
	F3	631	686	259	-	418	-	643	572	-	369	569
Trunk rotation	S1	-	405	621	-	479	184	400	504	-	589	525
	F1	-	388	580	-	460	212	349	536	-	600	525
	F2	-	366	577	-	491	253	369	512	-	558	515
	F3	-	402	686	-	537	180	354	509	-	615	509
Trunk twist	S1	-	-	-386	764	752	-	-	-	775	157	1021
	F1	-	-	-239	671	643	-	-	-	759	159	1003
	F2	-	-	-209	1089	452	-	-	-	736	244	979
	F3	-	-	-279	922	778	-	-	-	762	174	1017

F2 was the slowest at 530 deg/s. Angular velocity of thigh rotation for S1 during ascending phase of PoF was 387 deg/s and F2 had the fastest average angular velocity of thigh rotation at 397 deg/s, while F1 was the slowest at 352 deg/s. Angular velocity of thigh rotation for S1 during descending phase of PoF was 571 deg/s and F1 had the fastest average angular velocity of thigh rotation at 586 deg/s, while F2 was the slowest at 559 deg/s. Angular velocity of thigh rotation for S1 during BTO was 672 deg/s and F1 had the fastest average angular velocity of thigh rotation at 812 deg/s, while F3 was the slowest at 631 deg/s. Angular velocity of thigh rotation for S1 during HTD was 671 deg/s and F3 had the fastest average angular velocity of thigh rotation at 686 deg/s, while F1 was the slowest at 622 deg/s. Angular velocity of thigh rotation for S1 during HTO was the fastest at 278 deg/s, while F2 was the slowest at 212 deg/s. Angular velocity of thigh rotation for S1 during LD was 371 deg/s and F1 had the fastest average angular velocity of thigh rotation at 460 deg/s, while F2 was the slowest at 135 deg/s.

Change in angular velocity of trunk rotation

Average angular velocity of trunk rotation for S1 during BC was 184 deg/s and F2 had the fastest average angular velocity of trunk rotation at 253 deg/s, while F3 was the slowest at 180 deg/s. Average angular velocity of trunk rotation for S1 during PrF was the fastest at 400 deg/s, while F3 had the slowest average angular velocity of trunk rotation at 349 deg/s. Average angular velocity of trunk rotation for S1 during HC was the slowest at 504 deg/s, while F1 had the fastest average angular velocity of trunk rotation at 536 deg/s. Average angular velocity of trunk rotation for S1 during ascending phase of PoF was 589 deg/s and F3 had the fastest average angular velocity of trunk rotation at 615 deg/s, while F2 was the slowest at 558 deg/s. Average angular velocity of trunk rotation for S1 during descending phase of PoF was the fastest at 525 deg/s, while F3 was the slowest at 509 deg/s. Average angular velocity of trunk rotation for S1 during HTD was the fastest at 405 deg/s, while F2 was the slowest at 366 deg/s. Average angular velocity of trunk rotation for S1 during HTO was 621 deg/s and F3 had the fastest average angular velocity of trunk rotation at 686 deg/s, while F2 was the slowest at 577 deg/s. Average angular velocity of trunk rotation for S1 during LD was 479 deg/s and F3 had the fastest average angular velocity of trunk rotation at 537 deg/s, while F1 was the slowest at 460 deg/s.

Change in angular velocity of trunk twist

Average angular velocity of trunk twist for S1 during PoF was the fastest at 775 deg/s, while F2 was the slowest at 736 deg/s. Average angular velocity of trunk twist for S1 during ascending phase of PoF was the slowest at 157 deg/s, while F2 was the fastest at 244 deg/s. Average angular velocity of trunk twist for S1 during descending phase of PoF was the fastest at 1,021 deg/s, while F2 was the fastest at 979 deg/s. Average angular velocity of trunk twist for S1 during HTO was the fastest towards negative at -386 deg/s, while F2 was the slowest at -209 deg/s. Average angular velocity of trunk twist for S1 during Peak was 764 deg/s and F2 had the fastest average angular velocity of trunk twist at 1,089 deg/s, while F1 was the slowest at 671 deg/s. Average angular velocity of trunk twist for S1 during LD was 752 deg/s and F3 had the fastest average angular velocity of trunk twist at 778 deg/s, while F2 was the slowest at 452 deg/s.

Discussion

The purpose of this study was to explore key kinematic variables of Yeo Seojeong vault by analysing series of vaults (1 successful and 3 unsuccessful) performed by YSJ in order to provide technical support for YSJ and coaches to develop successful training strategy as well as promote adoption of the technique among gymnasts. In this regards, we have selected the variables used by previous studies (Song and Park, 2016; Takei et al., 1996, Takei, 2007). Currently, there are not many studies, which explored vault performance of world level gymnasts. However, group of Korean researchers have been consistently publishing study findings regarding world level male vault performance since 2012 (Park and Song, 2012, 2015; Song and Park, 2016; Song, 2017, 2018, 2019). These studies have used similar criteria with our study for analysis of kinematics, therefore we might be able to compare successful vault (S1) of our study to these studies, especially study by Park & Song (2012) which explored kinematics of YANG Hak Seon vault of male competition, as Yeo Seo Jeong vault is variation of YANG Hak Seon vault. Also, considering the fact the studies are scarce in this field, we could compare the kinematic variables from other sports which have similar movement characteristics such as pole vault, diving, and etc.

S1 was the vault performed by YSJ in 2019 Korea Cup, which was almost perfect except for the landing where YSJ moved one step left. S1 had relatively longer and higher post-flight in terms of vertical and horizontal displacement (2.62 m and 2.91 m) and also had faster rotation and twist velocity (775 deg/s) during post-flight. These are not comparable with YANG Hak Seon vault performed by Yang Hak Seon (YHS) from previous study (Park & Song, 2012), which has vertical and horizontal displacement of 2.89 m and 3.67 m, and twisting velocity of 991 deg/s (Park & Song, 2012). However, when we consider that height of YSJ is 9 cm shorter than YHS which allows YSJ twisting more easily, and also that Yeo Sejeong vault requires one less twist during the post flight than YANG Hak Seon vault, we could assume that vertical and horizontal displacement and fast rotation/twist velocity of the post-flight are likely the key factors for successful performance. In fact, previous studies showed that higher body COM and larger horizontal displacement are positively correlated with the score of vault (Farana & Vaverka, 2012; Takeiet al., 2003; Takei, 2007). We believe that the successful post-flight motion came from fast horizontal velocity at horse touch down while generating fast trunk rotation at horse contact. These have resulted fast thigh rotation during horse take-off as well as take-off angle exceeding 90 degrees which secured height as well as horizontally oriented body COM displacement during post-flight. Landing angle and trunk twisting angle at the landing are other possible candidates for successful Yeo Seo Jeong vault. S1 showed relatively large landing angle (50 degrees) as well as trunk twist angle (681 degrees) at landing compared to all of unsuccessful trials from our study and these are comparable to Yang Hak Seon vault which had landing angle of 57 degrees and trunk twist angle of 679 degrees. Indeed, as Yeo Seo Jeong vault requires two and a half twist to fulfil requirement, ability to generate large trunk twist angle is prerequisite for successful performance. Also previous study found that the higher height of body COM at landing is correlated with higher score (Farana et al., 2013; Takei et al., 2007).

F1 was the unsuccessful vault which landed on the mat and took a back step and then collapsed. There was no difference between F1 and S1 in terms of knee and hip angles at the landing, however F1 had the smallest landing angle and trunk twisting angle at landing (38 degrees and 650 degrees). This means F1 did not have enough body rotation as well as twist to complete execution of Yeo Seojeong vault. We believe that these lack of rotation and twist are due to relatively shorter post-flight time that YSJ did not have enough time to complete required rotation as well as twist. F1 approached the board relatively slow and had the low body COM, small horizontal displacement of body COM, and slow vertical velocity at every preparation phase, which were reflected on rather small post-flight. This means F1 relied only on the movement which attempted to accelerate thigh and trunk rotation during preparation phases instead of attempting to generate forceful propulsion for the pre-flight using springboard. Indeed, previous study stressed that the initial pre-flight values must be increased or the losses during horse contact must be reduced for greater take-off (Hiley et al., 2015). And the studies on pole vault, which shares similarities with vault up to the flight-phase, also suggested that generating great speed as well as take-off velocity to bend the pole sufficiently is critical to achieve great height (Hanley et al., 2022). We assumed that relying only on the acceleration of rotation during springboard contact caused hyperextension of hip joint through the horse take-off which hindered the propulsion for post-flight, rotation of thigh and trunk, and the twist of trunk.

F2 was also the unsuccessful vault which landed in a sitting position. When landing, F2 had knee angle of 118 degrees, vertical body COM of 0.57 m, landing angle of 44 degrees, and twist angle of 668 degrees. This means that the body was quiet bent while failed to plant the feet on the ground resulting in sitting down. Furthermore, F2 had small landing angle as well as not enough twist of trunk. This is not only a form break, but also a failed landing that may not be recognized as difficulty level as Yeo Seojeong vault due to the lack of twisting. One of candidates for the unsuccessful landing might be the lack of rotation and twist velocity during descending phase of post-flight. F2 had faster thigh rotation and trunk twist at the ascending phase of post-flight, however there was deceleration in these rotation and twist during descending phase. We presume that when YSJ was performing F2, she kinaesthetically sensed slower horse take-off as well as improper trunk and thigh rotation, which forced her, as a compensation, to attempt to maintain the high speed of thigh rotation as well as increasing the speed of twisting in order to complete the execution of the vault. She did this by kicking the leg too early from the ascending phase of post-flight to retain speed of thigh rotation while wrapping the upper trunk with arms (narrowing shoulder joint) to increase speed of trunk twist. In other words, it looks like YSJ attempted to twist the trunk at the horse take-off, where her head was pointing downwards, which limits her ability to twist. Furthermore, even though YSJ wrapped the trunk with arms to speed up the twisting, she lost her momentum to twist after the Peak, where head was pointing upwards. Thus, we believe that the factors, which caused weak propulsion off the horse, are slow approaching speed to the board, touching down board with bent body posture, slower vertical velocity off the board due to not fully extending shoulder joints, failing to generate enough propulsion off the board, and improper trunk rotation at horse contact leading to inefficient blocking. As we have discussed earlier, fast horizontal velocity towards board is an important determinant for successful vaults, because energy built up during the running phase will be converted to linear and angular momentum at board touch down (Fernandes et al., 2016). As illustrated in the studies anlaysing diving performances, maintaining relatively straight trunk posture (high COM) during board touch down is critical because it increases rotation potential (Koschorreck & Mombaur, 2012; Mccormick, Subbaiah, & Arnold, 1982; cited in Kim et al., 2019) and also allows gymnast to quickly rebound off the board (Uzunov, 2011). Fully extended shoulder during board touch down is another important factor. A study by Hiley et al. (2015), which tested optimal touch down technique to maximise rotation potential and angular momentum for post-flight, illustrated that shoulder angles of 180 degrees had the greatest rotation potential as well as angular momentum for post-flight compared to angles of 137 degrees and 128 degrees.

F3 was the unsuccessful vault, which YSJ kept twisting during landing and then collapsed on the left side. Landing angle for F3 was 48 degrees while twist angle was 680 degrees that almost fulfilled twisting requirements for Yeo Seojeong vault, however YSJ could not control moment of inertia leading to loss of balance. This is because YSJ failed to make body upright at the horse take-off with short horizontal displacement and vertically oriented post-flight, which had negative effect for the trunk rotation at descending phase. Takei et al. (2007), in thier study, have shown that higher score vault had slightly arched body in line with shoulder and hand at the horse take-off while lower score vault had flexed body only half-way to the handstand, where F3 illustrates characteristic of lower score vault. Although achieving great height is crucial in post-flight, height alone might not ensure adequate time for rotation and twist. Horizonatal displacement also holds significant importance (Lee et al., 2012; Park, 2020; Takei et al., 2003; Takei, 2007), however F3 failed to generate longer horizontal displacement. F3 showed fast horizontal velocity at board take-off, small rotation angle of hip and trunk, and lower body COM at the horse touch down, and small horse touch down angle, which made powerful blocking at the horse contact leading to strong propulsion off the horse. Although, this allowed YSJ to have relatively longer flight time, she could not obtain greater angular distance of trunk off the horse, which hindered rotation during the post-flight.

Apart from whether vaults were successful or not, we should pay attention to neck angle at the moment of Peak. Because, in order to increase the twisting velocity, the chin must be pulled in to make a body forming one axis (vertical) from the feet to the head to reduce the moment of inertia to speed up the angular velocity. In other words, the moment of inertia can be minimised when the neck joint angle is close to 180 degrees. However, neck joint angles for all trials, including S1, were less than 160 degrees. This means that YSJ could not pull the chin in, leading to have larger moment of inertia, which is considered to have an adverse effect on twisting.

After careful appraisal of our results authors and coaches agreed that YSJ needs to improve core strength which will help her to perform Yeo Seojeong vault consistently with benefit of injury prevention. Core strengthening exercise would benefit YSJ in terms of building up internal muscle, improving strength as well as body balance (Brill & Couzen, 2008; Willdson et al., 2005). Core exercise program should involve dynamic resistance movement, for example, sled drag and farmer’s carry, which will allow YSJ to maintain stiffness against sudden force exerted on her body.

A limitation of our study is that we only analysed four vaults (1 successful, 3 unsuccessful) without the statistical analysis. However, this was the only option we had since Yeo Seojeong vault can only be performed by YSJ. Future research should collect more successful Yeo Seojeong vault, which will allow us to run statistical analysis to explore factors associated with successful vault in more details.

Conclusion

In conclusion, the purpose of this study was to explore key kinematic variables of Yeo Seojeong vault by analysing series of vaults (1 successful and 3 unsuccessful) performed by YSJ in order to provide technical support for YSJ and coaches to develop successful training strategy as well as promote adoption of the technique among gymnasts. To sum up our findings of kinematic analysis, successful Yeo Seojeong vault was possible when YSJ had fast horizontal velocity at horse touch down as well as fast trunk rotation during horse contact, these allowed her to have faster thigh rotation and take-off angle exceeding 90 degrees at horse take-off resulting to reach maximum height and the length during post-flight. Together with higher and longer post-flight, faster rotation and twisting warranted the successful completion of Yeo Seojeong vault. From the unsuccessful vaults, we found that slow horizontal velocity and bent body posture at board contact as well as low body COM, small horizontal displacement of body COM, and slow vertical velocity at every preparation phase had adverse effect on the horse take-off, i.e. improper blocking, weak propulsion, and etc. These resulted rather insufficient post-flight with deceleration of rotation and twisting in descending phase of post-flight leading to insecure landing. Neck angle not reaching 180 degrees is another factor hindering successful performance. Prescription of core exercise program, which involve dynamic resistance movement will aid YSJ to have consistent performance while preventing her from injuries.

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Author Contributions

Conceptualization: Jooho Song & Don Hyung lee
Data curation: Jooho Song
Formal analysis: Jooho Song & Don Hyung lee
Investigation: Jooho Song
Project administration: Jooho Song
Writing-original draft preparation: Don Hyung lee
Writing-review and editing: Jooho Song & Don Hyung lee

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