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Technical Report

Kinematic Analysis of the Centre of Mass in the Back Handspring: A case study.

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ABSTRACT

The purpose of this study was to analyze the back handspring from a round off in gymnastics via kinematics. A secondary purpose was to explore the use of an optoelectronic system in studying the nature of this skill. Five female gymnasts, with differing levels of expertise volunteered as subjects. An optoelectronic system (Vicon Motion 460) was employed (100Hz). A 45 point three-dimensional model was used to characterize the body, and descriptive analyses were performed. The results demonstrated that the most accomplished gymnast achieved a greater take off horizontal velocity into the back handspring (3.4 $m.s^{-1}$) and from the hands support phase (2.2 $m.s^{-1}$). The most advanced gymnast showed a higher take off vertical velocity from hands support (1.0 $m.s^{-1}$) and higher flight trajectory from her hands (6 cm). The less skilled gymnasts all demonstrated a serious flaw by showing a marked descent during the flight phase from the hands. They showed inappropriately long first flight phases (67 and 75.3 cm), sacrificing distance during the second flight. The more expert gymnast demonstrated fewer general technical errors. This study demonstrated that infra red optoelectronics optoelectronic systems are helpful in reporting kinematics performance deficiencies and determining the biomechanical reasons for superior performances.

Key Words: Acrobatics, Flic flac, Tumbling, Skill learning, Biomechanics.

Keep the abstract below 500words.

INTRODUCTION

Artistic gymnastics has received considerable attention from biomechanics investigators (1). Kinematic analysis of gymnastics informs in two ways, scientists learn about the nature of gymnastics movement, and it provides a framework within which coaching and judging analysis can be objectively interpreted (2,3). Most gymnastics tumbling studies involve kinematics of difficult skills such as double somersaults and somersaults with twists. This approach serves elite gymnasts and performer coaches by enhancing understanding of skills that can help to lead to higher scores. However, even elite gymnasts must rely heavily on basic gymnastics skills. Thus, there is a disparity between kinematic analysis of basic skills such as the back handspring (BH) (i.e., flic flac) and the round off (RO) and much more advanced skills. One of the most important skills in artistic gymnastics is the BH (4). As a form of `acrobatic locomotion` the BH consists of a backward jump and flight onto the hands and then a quick push from the hands to a second flight phase to land on the feet. The basic BH begins and ends in a standing position (Figure 1). The first flight phase of the BH should be relatively long and low minimizing height and flight. The BH does not add points to a gymnast's routine due to its basic nature, but it is crucial to the performance of higher level skills. The BH can be performed poorly enough to cost the gymnast points, in fact it is primarily used as a stepping stone or accelerator movement from a round off to difficult somersaults and somersaults with

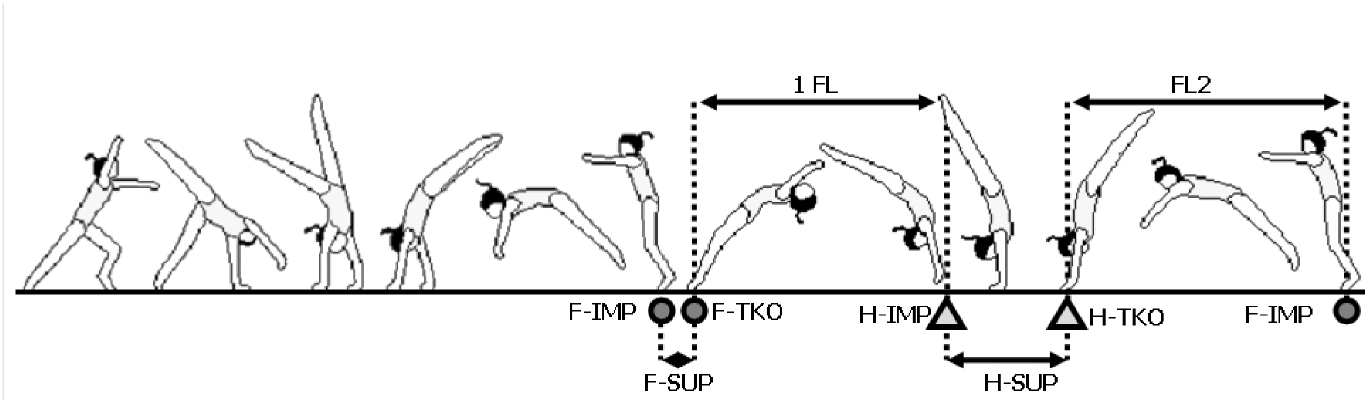

Figure 1. Shows the back handspring from the round off. The instants of impact and take off relative to feet and hands identified the four phases of feet support (a), 1 flight (b), hands support(c) and 2 flight (d).

twists. Due to the ubiquitous nature of the BH, proper technique is also important in efforts to prevent injury (5,6,7,8,9).

There is a paucity of information on the kinematics of the BH. Koh et al (10,11) and Davidson et al (12) studied the kinetics of the BH via ground reaction forces during the support phase on the hands. Payne and Barker (13) and Seeley and Bressel (14) studied the kinetics of the skill phase that often precedes the BH in a tumbling pass. In particular they focus on the final action of the round off (e.g. snap down). Grassi et al (15) analyzed the BH using optoelectronic methods, but only reported the markers trajectories.

The importance of the BH cannot be understated because as the round off and BH series work becomes faster and more efficient power is generated that allows increasingly more difficult skills to be performed. As such, the methodology for gaining kinematic information about the BH, and commensurate understanding of the skill, should invoke the most sophisticated and thorough investigation techniques. Therefore, it is clear that an analysis of the entire body and the path of the center of mass (COM) are warranted. Earlier investigations with more limited equipment provided some insights but often could not rival a coach's visual analysis.

The purpose of this study was to characterize the general motion of the BH though the analysis of the COM movements recorded in 3-dimentions. The information derived from this study should assist scientists in furthering information on the BH, coaches by providing new and sophisticated information on a crucial skill, and technologists by showing the use of an optoelectronic system with a relatively stationary rotational movement.

METHODOLOGY

Subjects

Five Italian female gymnasts ranging in age from 10 to 14 years, competing for two local gymnastics clubs, volunteered to participate. Informed consent and assent were obtained in writing conforming to University of Bologna policy on research involving human subjects. These gymnasts were selected based on their level of proficiency in tumbling. The Italian Gymnastics Federation (FGI) ranks gymnasts in categories A, B, C, and D, with A being the highest or most proficient. Gymnast 1 was a Level A (1A) and a Junior National Team member. Gymnast 2 (2B) was B level. Gymnasts 3 and 4 were Level C (3C and 4C, respectively). Gymnasts 5 (5D) was a novice gymnast ranked as a Level D. The athletes were assessed anthropometrically for height, body mass (Table 1), leg length, knee diameter, ankle diameter, bi-iliac breadth, elbow diameter and wrist diameter. The anthropometric data were later used for the automatic determination of the location of the COM of the body.

Procedures

Gymnasts performed their BHs on a standard 5 cm thick tumbling mat composed of polyethylene foam encased in a vinyl cover approved by the FGI. The motion of the gymnasts was captured in three-dimensions using external spherical markers (14 mm diameter) and analyzed by an optoelectronics system (Vicon Motion System 460, Vicon Oxford Metrics, Oxford, England). The system consisted of six infrared cameras with a maximum resolution of 300.000 pixels in the visual field and sampling performed at 100 Hz.

The motion capture volume was 4 x 2 x 3 m (video). The absolute error in this camera configuration was measured with a 25 mm diameter marker and found to be approximately 1 mm. The gymnast's body was characterized by 45 reflective markers placed in defined positions identifying joints and segment locations (Figure 2). COM was defined as the centroid of a 15-segment model (head, thorax, 3-segment arms, pelvis, and 3-segment legs). Thirty-five markers were applied according to the standard gait kinematic model (Plug-In-Gait, Vicon Peak®, Oxford, UK) (Figure 2) The lower body model is described by Davis et al (16), Kadaba, Ramakrishnan and Wootem (17) and Ramakrishnan and Kadaba (18). The upper body segment definition is based on the Hay`s model (19). Despite this model has not yet been evaluated, Gutierrez, Artonek and Saraste (20) showed that it is accurate and reliable in measuring COM motion as the well-established method based on the ground reaction force integration. In order to solve the marker occlusion problem created by the gymnast's limbs moving over and thus covering underlying markers, an additional ten markers were applied. The Plug-In-Gait marker set and the additional marker set are shown in Figure 2.

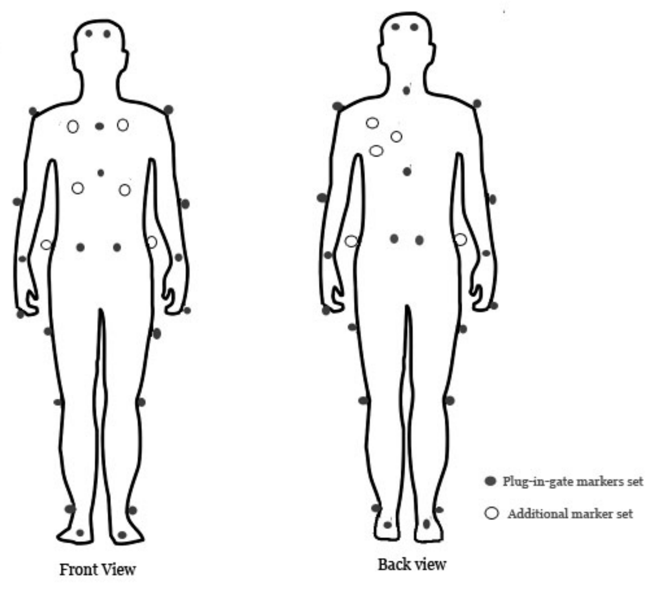

Figure 2- Shows the marker sets used to characterize the gymnasts` body in a 3-dimentional virtual environment. The black markers identified the Plug-In-gate marker set; the white markers identified the additional marker set used to increase the visibility of the body during the rotational movements. The markers were 14 mm in diameter.

Additional markers (2) were placed between the deltoid and the pectoral muscles over the coracoid process on both sides. Two anterior markers were also placed on the lowest full rib directly below the nipple. Three markers were placed on the left scapula, one at the superior-medial angle, one at the inferior angle, and one centered on the axillary border. Finally, two markers were located on each side of the pelvis at the superior crest of the ilium.

Gymnasts were allowed a self-selected warm up and then performed 10 repetitions of BH. The best trials, in terms of gymnastics execution, evaluated by means of the qualitative analysis of two federal judges, and marker recognition, were selected for further analysis.

The COM was automatically calculated by the Vicon's software using the Winter method (21). Approximately 200 frames from foot impact (IMP) of the final phase of the RO to the last foot IMP at the end of the BH from each trial were analyzed. Each trial was broken into four phases which were defined as: a – feet support (F SUP) following the RO, b – first flight (FL) phase from feet to a subsequent landing on the hands, c – Hands support (H SUP), and d – second flight phase (2FL) from the hands to the feet (Figure 1).

Data Analyses

All kinematic variables, including position, displacement and velocity were obtained from the data acquisition software's report functions. The angle variables were determined by further calculation involving separate algorithms. Temporal information was derived from frame counts between events of interest and was expressed in time units of seconds and in percentages.

COM horizontal component path and trajectory information were calculated from horizontal and vertical displacement data. The COM vertical component information was extrapolated from the COM trajectory calculations. In order to further characterize the COM vertical component movement, the foot and hand support phases were divided into eccentric and concentric phases. The eccentric phase was defined as the period from initial hand or foot contact to the instant where the COM was at its lowest point. The concentric phases began at the end of the eccentric phase and concluded on hand or foot departure from the mat. The flight stages were broken down similarly into two phases. The first phase consisted of the upward motion of the COM from a departure following the hand or foot contact, while the second phase was defined as the downward movement of the COM from the peak of its flight trajectory to the first frame of foot or hand contact. Temporal data were also determined for each phase. Velocity data of the COM were calculated from the horizontal and vertical velocity components by standard methods.

An overall body angle was determined as the angle between the horizontal and a line running from the toe(s) or fingers to the COM measured in a counterclockwise direction.

In keeping with the descriptive nature of this case study, statistical analysis consisted of descriptive statistics of all variables (mean and standard deviation) and percentages.

Temporal Analysis

The average total duration of the BH was 0.78 ± 0.03 s (table 2). The novice gymnast performed the skill the quickest (0.74 s). The FL required approximately 35% of the entire skill while the 2FL required 29% of the entire movement.

Horizontal Displacement

The total mean distance traveled of the COM during the entire skill was 1.730 ± 0.155 m (Table 3). Also of note, the COM continues to move backward horizontally during the support phases of the hands and feet. The average movement of the COM was greater during the F SUP than during the H SUP. The horizontal displacement of the COM was also greater during the 2FL than during the FL.

Vertical Displacement and Durations of COM during Support Phases.

During the H CONC phase there was a wide variability among subjects. (Table 4) Note that the first three subjects showed a relatively short ECC phase followed by H CONC while the last two subjects showed almost no ECC phase and an absent eccentric/concentric transition resulting in a collapse during hand support and further fall to the feet.

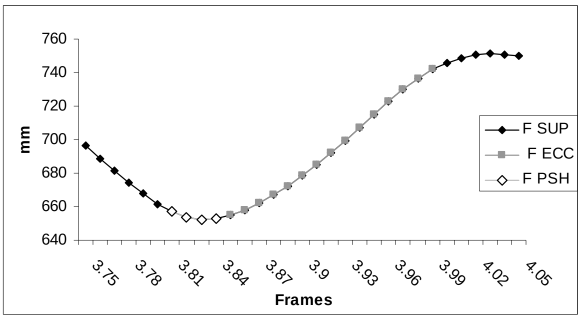

Figure 3. Vertical displacement of the centre of mass of the expert gymnasts 1A

Figures 3 and 4 show the presence of a eccentric/concentric transition in Subject 1A (Figure 5) while Subject 5D (Figure 4) shows an absence of the transition phase.

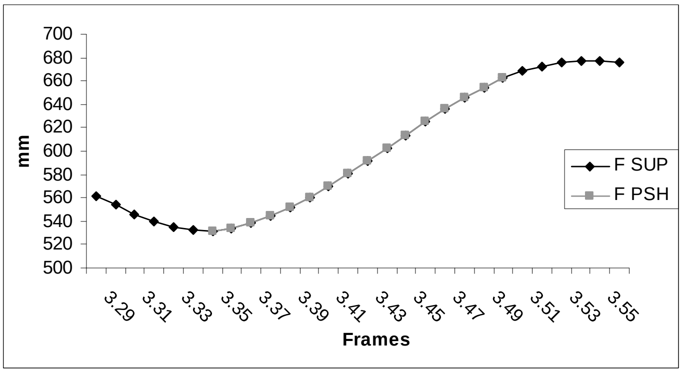

Figure 4. Vertical displacement of the centre of mass of the novice gymnasts 5D.

Vertical Displacements and Durations of the COM during Flight Phases

Table 5 serves to show the wide variability in all the relevant variables. Interestingly, only the more expert gymnast (1A) showed a positive value above zero for 2FL up. This further emphasizes the overall postural collapse of the hand support phase of the other gymnasts.

COM Horizontal Velocity

After the RO at the F IMP phase the average horizontal velocity is 2.0 m.s^{-1} ^{n} (Table 6), while during F SUP the athletes were able to increase their horizontal velocity to a mean of 3.4 m.s^{-1} at take-off from the feet (F TKO). Horizontal velocities slowed during H SUP considerably. By completion of the BH the horizontal velocities were still slower than the velocities achieved after the F SUP phase following the RO. The most expert gymnast was able to conserve more horizontal velocity of the COM than the less experienced gymnasts.

COM Vertical Velocity

The TKO values show that only one athlete was able to achieve a positive velocity during the H TKO (Table 7).

Angle Analysis

Table 8 shows the angles of the body in the sagittal plane with a vertex at the athlete's toes/hands. It is defined as the angle of the line connecting the COM to the point of contact which the mat (feet or hands). Note that the angle of the body during hand departure (H TKO) that three of gymnasts showed angles greater than 100 degrees while the two most advanced gymnasts showed departure angles closer to vertical.

DISCUSSION

The results of this study showed that the BH from a RO without a running approach was fast taking less than a second to complete. During this rapid skill the periods of longest duration were the two flight phases, from the landing of the feet of the RO to hand support (0.27 s ± 0.05) and from hand support back to a feet landing (0.22 s ± 0.05). The shortest phase was the H SUP phase (0.12 s ± 0.02) separating the two flight phases. Horizontal distances of the BH were largest for the more experienced and expert athlete (1.914 m) while the shortest distance was shown by the novice gymnast (1.505 m).

Tumbling is a `form of locomotion` that involves both hands and feet, not simply feet. If we think of tumbling as something similar to an `acrobatic-run` then the goals of the BH should be clear and similar to a running stride. In the case of the BH, alternate foot contacts are replaced with simultaneous hands and feet contacts. Run speed is controlled by stride length and stride frequency (22). A similar situation arises in the BH from the RO. The athlete should strive to both cover a large distance and perform the BH at relatively high horizontal velocities. There is an optimal combination of both distance and speed in a running stride and in a BH. An athlete who performs a BH with high speed while sacrificing distance of travel will not achieve overall effectiveness in tumbling (2). The athlete who achieves large flight distance must also achieve a relatively high flight trajectory resulting in a pronounced downward component velocity and force that must be arrested at hands and feet contact and reversed to continue subsequent movements (4,13). This study demonstrated at a descriptive level that the most accomplished gymnast (1A) achieved a greater horizontal component velocity (F TKO 34 $m.s^{-1}$ and H TKO 2.2 $m.s^{-1}$) without resorting to a higher first flight phase (1FL 0.94 cm), while the second flight phase showed that she was attempting to arrest the movement thus increasing the height of this phase (2FL 6.00 cm). A tumbling pass where the BH leads to a subsequent somersault the 2FL should be lower and usually longer to place the feet in an optimal position for the subsequent take off. The most accomplished gymnast showed a marked difference in her second flight phase by falling to her H SUP less rapidly (vertical velocity = -0.1 $m.s^{-1}$) than the less accomplished gymnasts who ranged from -0.4 $m.s^{-1}$ to -0.9 $m.s^{-1}$. Gymnast 1A showed a higher take off vertical velocity from her H SUP (1 $m.s^{-1}$), while less accomplished gymnasts showed vertical velocities that were slightly negative indicating that they fell rather than rose from H SUPP. The technical problem described above has been well known in gymnastics for some time (4,6,7,9,13).

Continuing the analogy of "tumbling as running" the BH becomes analogous to running strides. If the athlete wants to perform a skill following the BH that requires relatively large amounts of somersault rotation then the athlete needs to emphasize the horizontal component velocity such that the "trip effect" of stopping the feet on the floor causes the COM to pass over and above the feet at such a high velocity that somersaulting is emphasized (23). If the athlete wants to perform a high somersault without an over abundance of angular momentum, then the athlete may have a slightly higher BH trajectory in both flight phases in order to slow the somersault and emphasize a vertical direction of the jump thus increasing flight time while slowing the somersault. The reasoning above is evident in the difference between the gymnasts' horizontal displacements of the two flight phases where just athlete 1A was able to cover a relatively large horizontal distance of 70.9 cm in comparison with the other gymnasts' 2FL displacements of approximately 32 cm. The data show that the lesser experienced gymnasts made common technical errors, both gymnasts 2B and 3C performed the 1FL phase too long (67 and 75.3 cm respectively) while sacrificing the distance of the second flight phase (2FL, approximately 43 cm). This would be analogous to running a long stride on one leg and a short stride on the other.

In this study, the link between performance differences and goal differences is not as clear as the analogy above. The primary reason for performance differences in these subjects was more likely the marked differences in skill and ability (6,7,9). However, it was interesting that the more expert gymnasts also showed less pronounced deficiencies such as some counterproductive velocity, less horizontal displacement distances, and overall poor abilities in arresting and reversing hands and feet support phases. For example, the transition of the COM path during the F ECC to F PHS (-0.46 cm and 8.94 cm, respectively) was present only in athletes 1A and 3C. These athletes used a countermovement action involving a more sophisticated stretching-shortening cycle movement which usually provides more net force with less energy expenditure (1). This action is evident in the negative displacements of the COM of -0.46 and -0.30 cm in the two best gymnasts, 1A and 3C, while the other gymnasts showed zero displacement during the F ECC phase. The amortization of the impact and subsequent transition to a jump from the feet is a sophisticated movement pattern that requires years of practice in gymnastics (24,25). However, these movements are optimization problems in that too much negative displacement is hard to overcome and too little negative displacement during impact will fail to stretch the relevant muscles and connective tissues (23).

An additional example of the separation of the more expert gymnasts from those with less ability comes during the second flight phase (2 FL). The 2 FL phase represents the period when the gymnast modifies her horizontal and vertical displacement and velocity characteristics in order to obtain a superior result in the subsequent skill. In this study, the gymnasts did not perform a skill following the BH, but the potential for subsequent skills is evident. Only the most experienced gymnast was able to raise her COM (6 cm) during the 2 FL. The other gymnasts all showed a marked descent that would be very difficult to reverse and thus rise into a subsequent somersault of any type. The problem outlined above is also evident in the angle data which showed that the best gymnasts departed from their hands nearer vertical (96°). The higher angle of departure would allow the gymnast to rotate farther during the subsequent flight phase (2 FL) and thus arrive in a better position on her feet for subsequent skills (4,13).

CONCLUSIONS

This study demonstrates that biomechanics analysis of individual athletes is helpful both for reporting to coaches and in discovering potential reasons for superior and inferior performance. The data provided here indicate that differences in expertise are relatively easy to identify though 3 dimensional analysis making communication between coaches and athletes simpler, easier and more efficient.

In terms of methodology the study shows how is possible to use an optoelectronics system to study in depth specific gymnastics skills in under control conditions.

Tables

Table 1. Showing the mass (Kg) and the Height (cm) of the gymnasts.

	Gymnasts				
Anthropometric Measurement	1A	2B	3C	4C	5D
Mass (kg)	34.0	37.0	30.0	51.6	27.0
Height (cm)	144.0	145.0	138.0	158.0	124.0

Table 2. Showing the temporal durations of the four phases of the back handspring expressed in seconds (s) and in percentage of the duration of the whole movement (Tot BH).

	Foot Support		**1 Flight**		**Hand Support**		**2 Flight**		**TOT BH**
	s	% BH	s	% BH	s	% BH	s	% BH	
1A	0.18	0.23	0.22	0.28	0.09	0.11	0.31	0.39	0.80
2B	0.17	0.22	0.27	0.36	0.11	0.14	0.21	0.28	0.76
3C	0.16	0.20	0.32	0.40	0.12	0.15	0.20	0.25	0.80
4C	0.16	0.20	0.32	0.40	0.12	0.15	0.20	0.25	0.80
5D	0.15	0.20	0.24	0.32	0.15	0.20	0.20	0.27	0.74
Mean	0.16	0.21	0.27	0.35	0.12	0.15	0.22	0.29	0.78
StDev	0.01	0.01	0.05	0.05	0.02	0.03	0.05	0.06	0.03

Table 3. Showing the horizontal displacement of the center of mass (m) during the four phases of the back handspring.

	Feet Support (m)	**1Flight (m)**	**Hand Support (m)**	**2Flight (m)**	**TOT**
1A	0.468	0.526	0.212	0.709	1.914
2B	0.455	0.670	0.235	0.314	1.673
3C	0.424	0.753	0.298	0.349	1.824
4C	0.481	0.499	0.434	0.320	1.734
5D	0.381	0.509	0.318	0.297	1.505
Mean	0.442	0.591	0.299	0.398	1.730
StDev	0.399	0.114	0.0871	0.175	0.155

Table 4. Shows the vertical displacement of the centre of mass (cm) during both the feet and hands support phases, with each subdivided into respective sub-phases (Eccentric and Concentric). The ECC phase is characterized by negative displacement (downward) while the CONC phase is characterized by a positive displacement (upward). The eccentric (ECC) and concentric (CONC) phases are included with their temporal characteristics (s).

	Feet ECC		**Feet CONC**		**Hands ECC**		**Hands CONC**	
	Vert Dipl(cm)	Time(s)	Vert Dipl(cm)	Time(s)	Vert Displ(cm)	Time(s)	Vert Displ(cm)	Time(s)
1A	-0.46	0.02	8.94	0.16	-0.14	0.01	4.51	0.08
2B	-0.08	0.01	13.33	0.16	-1.15	0.04	0.48	0.07
3C	-0.30	0.02	14.72	0.14	-2.43	0.05	0.14	0.07
4C	0.00	0.00	11.63	0.15	-3.12	0.07	1.08	0.05
5D	0.00	0.00	13.05	0.15	-0.59	0.03	3.10	0.12
Mn	-0.17	0.01	12.33	0.15	-1.49	0.04	1.86	0.08
SD	0.20	0.01	2.19	0.01	1.25	0.02	1.87	0.03

Table 5. Shows the vertical displacements (m) and phase durations (s) of the centre of mass of the gymnasts during the first and second flight phases.

	1Flight				**2 Flight**			
	Up (m)	Time(s)	Down(m)	Time(s)	Up(m)	Time(s)	Down(m)	Time(s)
1A	0.009	0.04	-0.069	0.18	0.060	0.10	-0.133	0.21
2B	0.028	0.06	-0.113	0.21	0.000	0.00	-0.089	0.21
3C	0.063	0.12	-0.125	0.18	0.000	0.00	-0.154	0.20
4C	0.001	0.04	-0.066	0.17	0.000	0.00	-0.115	0.17
5D	0.015	0.05	-0.100	0.19	0.000	0.00	-0.159	0.20
Mean	0.023	0.06	-0.095	0.19	0.012	0.02	-0.130	0.20
Stdev	0.024	0.03	0.026	0.02	0.027	0.04	0.029	0.02

Table 6. Showing the horizontal component velocities (m.s^{-1}) of the centre of mass during the instants of impact and take off relative to feet and hands support phases.

	RO Feet IMP (m.s^{-1})	**Feet TKO** (m.s^{-1})	**Hands IMP** (m.s^{-1})	**Hands TKO** (m.s^{-1})	**Feet IMP** (m.s^{-1})
1A	1.5	3.4	2.2	2.5	2.2
2B	1.7	3.4	2.3	2.2	1.8
3C	2.3	3.2	2.1	2.4	1.5
4C	2.6	4.0	1.8	2.2	1.9
5D	1.9	3.0	2.1	2.3	1.4
Mean	2.0	3.4	2.1	2.3	1.8
StDev	0.45	0.37	0.19	0.13	0.32

Table 7. Showing the vertical component velocities (m.s^{-1}) of the centre of mass during the instants of impact and take off relative to feet and hands support phases.

	RO Feet IMP (m.s^{-1})	**Feet TKO** (m.s^{-1})	**Hands IMP** (m.s^{-1})	**Hands TKO** (m.s^{-1})	**Feet IMP** (m.s^{-1})
1A	-0.3	0.4	-0.1	1.0	-0.3
2B	-0.1	0.9	-0.5	-0.1	-0.1
3C	-0.2	1.1	-0.9	-0.2	-0.1
4C	-0.1	0.5	-0.7	-0.5	-0.2
5D	-0.1	0.7	-0.4	-0.3	-0.2
Mean	-0.2	0.7	-0.5	0.0	-0.2
Stdev	0.09	0.29	0.30	0.59	0.08

Table 8. Shows the angles of the body (°) in the sagittal plane with a vertex at the athlete's toes/hands. It is defined as the angle of the line connecting the COM to the point of contact which the mat (feet or hands).

	RO Feet IMP (°)	**Feet TKO** (°)	**Hands IMP** (°)	**Hands TKO** (°)	**Feet IMP** (°)
1A	74	113	81	96	55
2B	75	110	75	92	57
3C	69	104	82	106	55
4C	70	105	76	105	57
5D	69	106	77	107	53
Mean	71	108	78	101	55
StDev	2.84	3.74	3.04	6.74	1.66

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REFERENCES

1 - Prassas, S., Kwon, Y.H. & Sands, W.A. (2006). Biomechanical research in artistic gymnastics: a review. Sports Biomechanics; 5, 261-291.

2 - George, G.S. (1980). Biomechanics of women's Gymnastics.; Englewood Cliff, NJ:Prentice Hall.

3- Sands, W.A. & McNeal J. (1999). Judging gymnastics with biomechanics. Sportscience; sportsci.org/Jour/9901/was.html.

4 - Yuen, G.E. (1991). The back handspring: comparison of kinematic variables of the center of gravity following three different hand placements. USGF Sport Science Congress Proceedings. 1, 34-38.

5 - Caine, D.J., Lindner, K.J., Mandelbaum, B.R., Sands, W.A. & Lindner, K.J. (1995). (ed). Gymnastics Epidemiology of Sports Injuries.Champaign, IL: Human Kinetics.

6 - Sands, W.A.(1994a). Flic flac drill. Technique. 14, 12.

7 - Sands, W.A.(1994b). Technique error in the flic flac: A drill to help fix the problem.Technique; 14, 10.

8 - Sands, W.A. (2000). Injury prevention in women's gymnastics. Sports Medicine. 30, 359-373.

9 - Sands,W.A. & McNeal J.R. (2006). Hand position in a back handspring (flic flac). Technique. 26, 8-9.

10 - Koh, T.J., Grabiner, M.D. & Weiker, G.G. (1992). Technique and ground reaction forces in the back handspring. American Journal of Sports Medicine. 20, 61-66.

11 - Koh, M., Jennings, L. & Elliott, B. (2003). Role of joint torques generated in an optimized Yurchenko layout vault. Sports Biomechanics. 2, 177-190.

12 - Davidson, P.L., Mahar, B., Chalmers, D.J. & Wilson B.D. (2005). Impact modeling of gymnastic back-handsprings and dive-rolls in children. Journal of Applied Biomechanics. 21, 115-128.

13 - Payne, A.H. & Barker, P. (1976). Comparison of the take-off forces in the flic flac and the back somersault in gymnastics. P. V. Komi Biomechanics V-B 1976; 1-B ed, 314-321. Baltimore, MD: University Park Press.
14 - Seeley, M.K. & Bressel, E. (2005). A comparison of upper-extremity reaction forces between the Yurchenko vault and floor exercise. Journal of Sports Science and Medicine. 4, 85-94.
15 - Grassi, G.P., Santini, T., Lovecchio, N., Turci, M., Ferrario, V.F. & Sforza, C. (2005). Spatiotemporal consistency of trajectories in gymnastics: A three-dimensional analysis of flic-flac. International Journal of Sports Medicine. 26, 134-138.
16 - Davis, R.B.I., Ounpuu, S., Tyburski, D. & Gage, J. (1991). A gait analysis data collection and reduction technique. Human Movement Studies. 10, 575-587.
17 - Kadaba, M.P., Ramakrishnan, H.K. & Wootten, M.E. (1990). Measurement of lower extremity kinematics during level walking. Journal of Orthopedics Research. 8, 383-392.
18 - Ramakrishnan, H.K. & Kadaba, M.P.(1991). On the estimation of joint kinematic during gait. Journal of Biomechanics. 24, 969-977.
19 - Gutierrez-Farewik, E.M., Artonek, A. & Saraste, H. (2006). Comporison and evaluation of two common methods to measure center of mass displacement in three dimensions during gait. Human Movement Studies. 25, 238-256 .
20 - Hay, J.G. (1973). The biomechanics of sports techniques. Englewood Cliffs, NJ: Prentice Hall.
21 - Winter, D.A. (1995). Human balance and posture control during standing and walking, Gait Posture 3 193–214.
22 - Bobbert, M.F., Gerritsen, K.G.M., Litjens, M.C.A & Van Soest, A.J. (1996). Why is countermovement jump height greater than squat jump height? Medicine and Science in Sports and Exercise. 28, 1402-1412.
23 - McNeal, J.R. & Sands, W.A.(2001). Drop jump performance in talent-selected female gymnasts. Journal of Strength and Conditioning Research. 15, 397.
24 - McNeal, J.R., Sands, W.A. & Shultz, B.B.(2007). Muscle activation characteristics of tumbling take-offs. Sports Biomechanics. 6, 375-390.
25 - Finni, T., Ikegawa, S. & Komi, P.V.(2001). Concentric force enhancement during human movement. Acta Physiologica Scandinavica. 173, 369-377.