SKILL ANALYSIS OF KICK AND HAND-PUSH ACTIONS
IN SELECTED SIDE-HORSE VAULTING STUNTS

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Abstract

In order to find certain suggestions for improvements in performances in vaulting stunts and in its skill instruction, kicking and hand-push actions of selected side-horse vaulting stunts were studied by use of cinematographical analysis technique. Ten college gymnasts volunteered as subjects who performed squat vault, handspring vault and front somersault vault for picture taking. Upon analyzing projected pictures, the center of gravity movements were traced, from which vector analyses of kicking and hand-push actions were attempted. The outcomes included the followings:

1. Better control of body position and momentum during the initial stages of the action
2. Improvement in the timing and coordination of the kicking and hand-push actions
3. Enhanced understanding of the relationship between body position and gravity center
4. Increased awareness of the importance of the initial phase in the performance of stunts
5. Guidance on the execution of specific movements

This study provides valuable insights for both athletes and coaches aiming to improve their performance in vaulting and related gymnastic activities.
1. **No single technical and/or mechanical premises to decide the successful performance were found.** The execution in one of the premises, such as preceding run, kick and hand-push would be compensated in other premises, and hence, the total performance would not be ruled by one.

2. **Satisfactory speed in preceding run to be carried over to kicking action and smoothness in the last step of the run would provide effective pre-flight.**

3. **Sharp kick and hand-push actions with short duration of time would provide effective pre- and post-flights, respectively.**

4. **The kicking for take-off is generally directed to down-backward, while the hand-push, to down-forward.**

5. **Forward rotatory move of the trunk in rotatory vaulting stunts is generally produced by fast preceding run followed by a down-backward kick, while the center of gravity trajectory would not be so different between rotatory and non-rotatory stunts.**

6. **In the case of non-rotatory stunts, the trunk starts to rotate forward in the first half of the performance, though such rotation is reversed in the latter half, by wiggling the hips and up-lifting swinging of the arms.**

### 1. Introduction

Human movement is so versatile that a movement performed by a person at a time may vary from any other movements he has ever made before. Yet it is such specific at certain phases of skillful activities that established skills and habits, are difficult to be changed. Analysis of skillful body movements, for this reason, may constitute analysis of the skill itself.

Mechanical analysis of body movements may be attempted for merely a scientific interest, but also for finding certain suggestions for skill instruction. As a matter of fact, a few examples of studies, the results of which may be used as useful suggestions for instructional techniques, have been reported in variety of sports. However, instructional and/or coaching suggestions for horse vaulting stunts in gymnastics, for example, have been more frequently provided from intuitional considerations by instructors and coaches than from results of scientific studies.

Certainly a performance is usually given by a gymnast who is not necessarily always concerned about the mechanics of the skill, rather he performs as a whole person to whom other suggestions from psychological and physiological viewpoints may be also necessary. Yet, certain mechanical considerations should provide opportunities to improve some aspects of the performance. For this reason, mechanical studies of various physical skills, for the purpose of finding certain general mechanical principles which govern the skill and of providing useful suggestions to improve performances, should be conducted more frequently.

Thus, in this study, certain side-horse vaulting stunts in gymnastics are taken into movie films for the purpose of mechanical analysis so that useful suggestions for improvement of performances and teaching techniques may be provided.
**Purpose of the Study**

The purpose of the study then is to analyze the mechanics of certain side-horse vaulting stunts in gymnastics by applying previously established experimental technique of cinematographical analysis, so that the sequential body movement throughout each of the stunts and the specific characteristics of the stunts may be explained by use of certain parameters, such as quality and quantity of force involved in various phases of each performance made by certain novice and advanced college gymnasts. Accumulation of such study results may be expected to make contributions towards more thorough understanding in variety of human movements involving certain skills.

**2 Methodology**

In order to analyze the mechanics of certain side-vaulting stunts in gymnastics, the processes of (1) stoop vault (SV-1~SV-7), (2) handspring vault (HS-1~HS-6) and (3) front somersault vault (YV-1 and YV-2) were selected for cinematographical analysis.

2.1. Subjects

Ten college gymnasts majoring in health and physical education at Tokyo Gakugei University, two males and eight females, whose carrier length in this sport ranged between three and six years, volunteered as subjects. The reason why experienced gymnasts were exclusively used for the experiment was because for beginners these stunts are rather difficult to perform.

During the performance, the female subjects wore tightly fitted gymnastic uniform and the male, shorts, for the benefit of the picture analysis to take place later. Further, certain landmarks of the body, such as wrist, knee and ankle of the camera side of each subject were taped for the same reason.

The subjects warmed up themselves properly to the point at which they would be on the top level physical condition for performance. The runway and vaulting board for the approach of vaulting as well as mats at the landing area were provided as in the manner a competition would take place. The vaulting horse was placed sideways, with its height being 120cm.

2.2. Picture Taking Devices

Each performance to be analyzed was taken into 16mm high speed movie films by use of a camera, produced by Bolex Co., West Germany. Using a tripod, the camera was set at an appropriate height, 120cm from the floor, and at a certain distance apart from the vaulting horse in the transverse direction to the pathway of the performer to be fully able to catch the performance within the camera view.

Fuji Neopan R 250 black-and-white positive film with its ASA being 250, each role having 100 feet of length, was used for entire picture taking.

While the accurate shutter speed of each picture taking needs to be determined for this
type of experiment, the shutter speed indicator attached to the camera body may not represent the value, especially at the early stage of shutter rotation because of the momentum the film role possesses from speed "zero" status. Because such differences between the actual shutter speed and the indicator control were observed to come up nearly 25% in speed rate in some circumstances during the pilot study, special consideration should be necessary.

The ball dropping device, then, to determine such shutter speed was applied for the experiments. Thus a ball to be used in baseball was dropped from a height of 150cm from the ground. Taking account on the time length necessary for this free dropping, calculating from the formula 1, \( t = \frac{h}{v_0} \cdot \frac{1}{g} \) sec. in all the present cases, and the number of frames for such dropping, the time length involved for each frame was obtained. For the purpose of ball-dropping devise, a 2m x 4m black board with white grid of 10cm square covering the surface was produced. The whole process of shutter speed determination was taken after T. K. Cureton\(^{3}\). Since the distances between the camera and the line of performance and between the line of the performance and the grid were known, three spots being in a line and the line of performance being in between the other two, the actual distances of body movements would be mathematically obtained by applying proportional distribution between the above values to the distances of the same, seen in the projected pictures.

All the performances filmed in this study were of symmetrical nature for the subject. In addition, all the objects to be analyzed here were movements of center of gravity and certain body segments within the sagittal plane. When the performance involves certain unsymmetrical movements, more camera(s) should be used for multidimensional analysis. In this study, such procedures were omitted.

The shutter speed of camera, during the "acceleration phase" of the film rotation process, which may be less than that during the "top speed phase," was estimated by analyzing the trajectory line of the center of gravity of the gymnast during vaulting stunts. The center of gravity of a body during certain flight movements should pass along the parabolic line of projection all the time. The time length for each frame of the film given by ball dropping technique should coincide with time length calculated from the obtained trajectory line. After examining both results, the shutter speed of camera at various phases of film role rotation was reconfirmed\(^{3}\).

2.3. Recordings

After developing the taken films, each frame was projected on a screen by use of a Kodak Analyst apparatus. The projected pictures were then drawn on sheets of tracing paper. More than 700 frames of pictures, out of 8000 which were taken for the current experiment, were made into drawings for mechanical analysis. In each drawing, other physical objects than the preformer's body, such as the vaulting horse, vaulting board, mats and the grid were included. Using the grid, drawn each time, the scale for each frame was determined after the converting process mentioned earlier.

When all the drawings were combined, the process of body movement along the time

* Formulae used for various calculations in the study are listed in Appendix.
would be shown, provided the resultant drawing looks simple. For this reason, drawings of every 8 or 10 frames, with some exceptions when necessary, were combined in each performance for analysis of sequential body movements.

3. Parameters

3.1 Sequential Movement of Body Segments

Sagittal movements of certain landmarks of the body, such as the ear, shoulder, hip, knee, ankle, elbow and wrist, all on the camera side of the subject, were traced in each performance. Then combining any adjacent three landmarks, the sequential changes in angles of extremities and trunk were also analyzed. Likewise, the changes in angle between the trunk and the vertical line, which would indicate the process of body rotation, were recorded.

3.2 Center of Gravity

The center of gravity of the body of the performer was estimated in each frame of drawing. The estimation of center of gravity in variety of complexed body position shown on the course of performance was made by applying methods proposed by Matsui (3), modified by the current investigator earlier (3).

3.3 Vector Analysis

Upon obtaining the sequential course of center of gravity movement in each performance, the velocity and acceleration of center of gravity movement at each moment may be obtained when the time length for each frame is taken into account. When the vertical distance between center of gravity positions at the moment of take-off and at the highest point during the pre-flight in a given vaulting performance is given, for instance, the vertical component of initial velocity for the pre-flight is, by applying Formula 2, determined. At the same time, the horizontal velocity of a projected object is always constant, and hence, the horizontal component of initial velocity for the same may be simply given, by applying Formula 3. Substituting above values into Formula 4, the initial aerial velocity of the center of gravity and its angle of take-off may be calculated. Likewise, the velocity and incidented angle, right before the kicking action for take-off is taken, would be calculated.

Elements of the initial velocity that the center of gravity obtained right after the take-off, when mechanical consideration is given, should be the combining result of elements of center of gravity movement right before the take-off and that of kicking force which the body, particularly the lower extremities, applies to the vaulting board. It is indeed an example of vector. Applying vector analysis procedure, the amount of kick at the take-off (though the unit being velocity) may be calculated, using Formula 5.

After finding the amount of kick at the take-off, amount of acceleration, or the quantity of shock that the center of gravity receives may be calculated by Formula 6, provided the time length of take-off is given. Taking the body weight of the subject and the gravity force into account, when using Formula 7, the amount of force the center of gravity
4. Results and Discussions

4.1. Analysis of Data

In this study, certain side-horse vaulting stunts in gymnastics were filmed for mechanical analysis and the loci of body segments and those of center of gravity were traced. In this manner, general characteristics of each stunt and specific characteristics of each performance may be clarified. Each frame of picture was drawn on sheets of paper, and these drawings, when sequentially combined, provided body moves in the time course. Representing fifteen sequentially combined pictures which were produced in this study, Figure 1 is presented, though in the figure, for avoiding complexed drawings, only drawings of every eight frames are included. Heavy line in the figure represents the locus of center of gravity, which appear to be consistent with mechanical principles.

The mechanical elements in each experimental performance, which were calculated from the analysis of drawings, sequential drawings and loci of center of gravity along the time

![Fig. 1 Sequential drawings of SV-4 with locus of center of gravity.](image)

![Fig. 2 Vector analysis of force exerted by the center of gravity at the moment of kicking and hand-push in SV-4.](image)
Table 1. Results of Mechanical Analysis of Vaulting Performances (Pre-Flight, or First Projectile).

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<tr>
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incidental movement (pre-take-off)
- velocity (m/sec)
- incidental angle (degree)

moment of kick (take-off)
- angle of backward lean (degree)
- center of gravity height (cm)
- time length (sec)
- speed of kick (m/sec)
- angle of kick (degree)
- acceleration (m/sec²)
- acceleration (x G)
- exerted force (kg)

initial flight (post-take-off)
- initial velocity (m/sec)
- initial flight angle (degree)
- maximum height of center of gravity in first projectile (cm)
- lifted height of center of gravity (cm)
- expected horizontal distance of first projectile (cm)
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<td>38.0</td>
<td>18.1</td>
<td>21.0</td>
<td>18.4</td>
<td>11.6</td>
<td>18.0</td>
<td>21.6</td>
<td>35.3</td>
<td>38.0</td>
<td>54.0</td>
<td>39.6</td>
<td>58.8</td>
<td>70.2</td>
</tr>
<tr>
<td>maximum height of CG in second projectile (cm)</td>
<td>204.0</td>
<td>204.0</td>
<td>204.0</td>
<td>185.9</td>
<td>189.0</td>
<td>189.0</td>
<td>182.0</td>
<td>204.2</td>
<td>206.0</td>
<td>165.7</td>
<td>213.2</td>
<td>252.0</td>
<td>259.2</td>
<td>213.9</td>
<td>246.7</td>
</tr>
<tr>
<td>expected horizontal distance of second projectile (cm)</td>
<td>158.0</td>
<td>174.0</td>
<td>220.0</td>
<td>158.3</td>
<td>180.3</td>
<td>157.5</td>
<td>164.5</td>
<td>214.2</td>
<td>183.6</td>
<td>125.7</td>
<td>151.8</td>
<td>300.6</td>
<td>262.8</td>
<td>215.0</td>
<td>311.8</td>
</tr>
<tr>
<td>First and Second Projectiles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total time length of flight (sec)</td>
<td>.7468</td>
<td>.8481</td>
<td>.8228</td>
<td>.7975</td>
<td>.8734</td>
<td>.8481</td>
<td>.8228</td>
<td>.7657</td>
<td>1.2362</td>
<td>1.392</td>
<td>1.651</td>
<td>.8949</td>
<td>.8764</td>
<td>1.3190</td>
<td>1.3007</td>
</tr>
<tr>
<td>first/second projectiles x 100(%)</td>
<td>43.75</td>
<td>53.33</td>
<td>52.94</td>
<td>52.94</td>
<td>81.25</td>
<td>75.00</td>
<td>56.25</td>
<td>63.16</td>
<td>62.50</td>
<td>45.65</td>
<td>66.67</td>
<td>74.47</td>
<td>81.40</td>
<td>52.63</td>
<td>48.84</td>
</tr>
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</table>
course, are listed in Tables 1 and 2. While various vector elements involved in the kick and hand-push in each performance are included in these Tables, such vector elements along the loci of center of gravity were drawn on other sheets of paper. An example of such vector analysis is demonstrated in Figure 2.

The changes in joint angles at shoulder, hip and knee, $\angle S$, $\angle H$, $\angle K$, respectively, during the time course of performance, in which the extension position being marked as 0°, are demonstrated in Figure 3. Then, upon measuring the angle of the trunk with vertical line in each drawing, the process of body rotation was analyzed. In order to examine the relationship between the angular velocity of trunk, AV (degree/sec), and the body length (maximum distance between two furthest body segments), BL (cm), were compared also in Figure 3.

![Graph](https://example.com/graph.png)

**Fig. 3** Sequential changes in shoulder ($\angle S$), hip ($\angle H$) and knee ($\angle K$) joints, body length (BL) and angular velocity of trunk rotation (AV) in the time course of SV-4 performance.
The analytical procedure in this study included 700 drawings, 15 sequential drawings, and 4,000 parametric data. Upon examining given figures and tables and obtained data, following discussions may be made.

4. 2. General Discussion on Vaulting

General principles governing vaulting event may be numerically described when one carefully examines the Tables 1 and 2. Speed of approaching running, for example, varies so widely that the fastest runner (HS-5) with 8 m/sec velocity, or equivalent to 13.5 sec/100m dash speed, shows more than twice as fast as a novice girl vaulter (SV-5), who actually made a significant preceding jump before the take-off action (incidental angle being 46 degrees). The case of SV-5 being an exception, the incidental angle, ranging between 0 and 25 degrees, did not show strong relationship with the skill itself, while greater speed of approaching running seemed to produce better performance.

The angle of backward body leaning, recorded as the angle between the level and the line connecting the center of gravity and the toes at the moment of kick, was found not to be necessarily consistent within an individual in different attempts, while all the recordings stayed within ± 9 degrees. The actual kicking time length appeared to be slightly longer than .100 second in each case, and the involved acceleration ranging between 2G and 7G, both values seem to be somewhat similar to the cases of somersault in tumbling and floor exercise events, as to compare with the previous reports by the present investigator. The direction of kick varied between 78 ~ 135 degrees (zero degree being straight forward at the level, and 90 degree, exactly downward), though generally, prevalent tendency was to kick slightly down-backward.

The amount of force exerted during the hand-push action within a time length of slightly less than .200 seconds appear to be nearly half of that in kicking. The difference in time length between kicking and hand-push and the differences in the velocities in preceding body moves may be two major factors for this tendency. The hand-push was generally directed to down-forward, (angle less than 90 degrees). Certainly in no cases it was directed to down-backward in the squat vault. Only exception to this principle was the front somersault vault (YV-1 and 2) which requires rather fast body rotation, using the opposite reaction of the hand-push.

As the kick was directed forward, the amount of force involved in kicking increases, while this direction is not likely to be the only influential element on the scale of the first projectile. When the velocity of preceding run is larger and the kick is directed down-backward, forward body rotation may well be provided and the projectile may become rather low and forceful. In contrast, when the running speed is slow and kick is directed down-forward, forward rotation is provided and the projectile may become short and high. It seems, no single factor determines the total performance, rather, each element probably interact each other to produce the total performance. In other words, there is no definite ideal type of kick, projectile, hand-push, or landing, but rather, only inbalanced mechanical distribution would cause a poor performance. Example of such poor performances are seen in HS-2, 3
and 4 in which time lengths of hand-push were particularly long, resulting in extremely small amount of acceleration in hand-push and in poor post flight, or second projectile.

The initial flight angle of the center of the gravity during the pre-flight ranged between 21.0 and 45.6 degrees and the initial velocity of the same, 5.4 and 11.6 m/sec. The kinds of vaulting stunt (whether rotatory or not) did not affect the scale of such parameters. The center of gravity trajectory during the preceding run—kick—pre-flight, does not vary according to the vaulting stunt, though in the case of long-horse vault (in contrast to the current method, side-horse vault), the result may be different. However, certain differences were observed in the rotational movements of the trunk and the lower limbs between the rotatory and non-rotatory stunts. For example, upon examining figures (not presented here except SV-4 due to the limited availability of space) to show the process of trunk rotation during the time course of each performance, it was noticed that in the non-rotatory vaults, certain wiggling actions at the hips are taken during the post-flight in an attempt to recover from the already-leant-front trunk before the landing.

The initial flight angle of the center of gravity during the post-flight ranged between 15.1 and 48.8 degrees and the initial velocity of the same, 3.2 and 9.8 m/sec. These values are slightly smaller than the case of the pre-flight. In general, a sharp hand-push with short time length of hand-placing resulted in large scaled post-flight, and hence, judged to be a better performance.

4.3. Body Forms

Figure 3 is an example of the graphs provided for analysis of body forms in each performance. In stoop vault pre-flight, the arms are swung forward to the point of shoulder stretching (full upperarm flexion) to produce uplifting of the body.

Since all the subjects who performed stoop vault were of novice level, arm swing moves during post-flight seemed to be rather far from satisfaction, i.e., decrement tendency of \( S \) curves in the latter half part of the vaulting corresponded with increment tendency of \( H \) curves, insignificant BL and \( H + K \) curves in the graphic expressions. In the ideal performances, theoretically, the \( H \) and \( H + K \) curves should come to 0° position once during the post-flight when BL would reach to its maximum value as would seen throughout the pre-flight. Such an ideal performance would be provided by proper hand-push action, i.e., strong down-forward push followed by forcible up-forward hand swing action. Changes in trunk angular velocity, in such a case, would be distinctively versatile.

Both of the front somersault were rather satisfactorily performed. In both cases, knees were always kept straight and sharp pike position was made to provide quick trunk forward rotation at the early part of the post-flight. While the body forms were nearly same each other, the scale of the flight was significantly greater in the case of YV-2. The major difference obviously came from the velocity of preceding run. Such being the case, variety of suggestions for skill improvement may well be drawn for each performance when similar mechanical analysis are provided.
4. Coaching Suggestions

Within the limitation of the experiment taken here in the present study, it seems that no single mechanical elements overwhelmingly rule the success of a performance, because variety of elements interact each other. However, certain instructional and coaching suggestions may be made from the discussions presented above.

In general, it was understood that the kick and hand-push actions in each performance may be controlled in relation with the preceding run and body rotation. However, a powerful preceding run may be the key for producing an effective kick. The last step of the preceding run before the kicking should not be a jump with a large vertical element, but rather, it should be of sliding type. A sharp kick, which may result in great kicking acceleration, may well be advantageous for an effective pre-flight. The direction of kick should be determined according to the kind of vault (rotatory or not), i.e., provided the center of gravity trajectory being the same, kicking down-backward would produce more body rotation. When provided that same body rotation is kept, kicking down-forward would produce greater height in pre-flight trajectory of the center of gravity.

Regarding the angle of hand-push, down-forward hand-push seem to be necessary for non-rotatory vaults, in contrast to slightly down-backward for rotatory vaults. A sharp hand-push, which may result in great hand-push acceleration, may be advantageous for an effective post-flight.

Teachers and coaches, when instructing vaulting events, may utilize such suggestions as mentioned above, because any bodily performance has certain aspects for mechanical considerations and the performers may be benefitted by such information.

5. Summary

Certain side-horse vaulting stunts in gymnastics were mechanically analyzed to find principles governing each stunt and to provide certain suggestions for skill improvement. That no single mechanical elements overwhelmingly rule the success of a performance and that the ideal performance may be sought after accumulating similar efforts were among the findings.

Appendix

Formula 1.

In the free falling object, the following relationship exists between the vertical distance of the center of gravity movement, h, and the time length involved, t;

\[ t = \sqrt{\frac{2h}{g}} \]

while \( g \) = gravity force.

Formula 2.

Likewise, the relationship between vertical element of velocity, \( V_y \), and the vertical distance, h, is;

\[ V_y = \sqrt{2gh} \]

Formula 3.

The horizontal element of the velocity in a projected object, \( V_x \), is always constant and is
calculated from the horizontal distance, D, divided by time length to move such distance, t;

$$V_x = \frac{D}{t}$$

**Formula 4.**

The initial velocity, $V_v$, and its projected angle, $\theta$, in the projected object are calculated as follows;

$$V_v = \sqrt{V_x^2 + V_y^2}$$

$$\tan \theta = \frac{V_y}{V_x}$$

**Formula 5.**

In order to obtain $\overline{BD}$ and $\beta$ in $\triangle ABD$, whereas $\overline{AB}$, $\overline{AD}$, $\alpha$ and $\theta$ are known, the following procedure should be taken;

$$\angle A = \alpha + \theta$$

$$AB = f = b + d$$

$$b = c \cos A$$

$$d = AD - c \cos A = f - b$$

$$a = c \sin A$$

$$\angle D = \tan^{-1} \frac{a}{d} = \tan^{-1} \frac{c \sin A}{AD - c \cos A}$$

$$\overline{BD} = e = \sqrt{a^2 + d^2} = \sqrt{(AD - c \cos A)^2 + (c \sin A)^2}$$

$$\beta = \angle D + \alpha$$

In the case of $b > f$

$$d = b - f = c \cos A - AD$$

$$\beta = 180 + \alpha - \angle D$$

**Fig 4**  Vector analysis of kicking and hand-push.

In vector analysis of kicking and hand-push actions:

- $f = \overline{AD}$: center of gravity movement prior to kick/hand-push ($A \rightarrow D$) m/sec
- $e = \overline{BD}$: direction and scale of center of gravity applied at kick/hand-push ($D \rightarrow B$) m/sec
- $c = \overline{AB}$: center of gravity movement after kick/hand-push ($A \rightarrow B$) m/sec

**Formula 6.**

The amount of acceleration an object receives, $a$, is determined by the following;

$$a = \frac{V_d}{t_0}$$

whereas $V_d$: difference in velocity of the object between before and after the impact,

$t_0$: time length of impact
Formula 7.

The amount of force, \( F \), an object receives an acceleration equals to the mass \( m=\frac{W}{g} \), whereas \( W \) stands for weight and \( m \), mass) multiplied by acceleration.

\[ F = ma = -\frac{W}{g} \times a \]

Selected References