A Three-Dimensional Analysis of Hurdle and Board Takeoff Techniques in Gymnastic Vaulting

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ABSTRACT

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The purpose of this study was to provide general and detailed kinematic features in performing the hurdle and takeoff from the board among beginning, intermediate, and advanced gymnasts, to look for advanced techniques of executing the hurdle and board takeoff, to contribute to the improvement of gymnast vaulting theories and techniques, and to provide practical recommendations for gymnastics instructors.

Forty male and female gymnasts were selected for this study. The male subjects were from the beginning, intermediate, and advanced skill levels, while the female subjects were from the intermediate skill level only. Two synchronized cameras operating at the rate of 60 Hz per second were used in this study for a three-dimensional analysis. The video pictures were processed by using the Peak5 system.

The study results indicated that advanced gymnasts not only had significantly faster horizontal velocities than the less skilled gymnasts, but presented better ratios on the efficiency of horizontal velocity utilization during the hurdle and board takeoff. The efficiency was found by a significantly smaller angular displacement of the leg and a smaller vertical velocity at the hurdle foot takeoff, as well as by a lower hurdle flight angle and a lower hurdle flight height.

The advanced gymnasts had an average hurdle distance of 2.78 meters, which was significantly longer than that of the less skilled gymnasts. In addition, the advanced gymnasts finished the hurdle distance with significantly less time than the low-skilled

gymnasts.

The advanced gymnasts also presented significantly faster relative movement of their arms and legs during the hurdle and board takeoff. They had a significantly shorter time during board contact. In addition, they coordinated their body segments better, and they took off from the board with significantly greater horizontal, vertical, and angular velocities than the low-skilled gymnasts.

It was concluded that the advanced gymnasts generally involved their arms, legs, and trunks more actively, more efficiently, and with better timing and coordination than the less-skilled gymnasts during the hurdle and board takeoff.

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TABLE OF CONTENTS

TABLES

FIGURES

Figure | Page

APPENDICES

APPENDICES Page

CHAPTER 1

Introduction

Vaulting, as an event in both men's and women's gymnastics, has experienced rapid development during the last three decades. Many changes have taken place in vaulting, such as different requirements for both compulsory and optional vaults set by the Federation of International Gymnastics, improved vaulting equipment, increased biomechanical research on vaulting, innovative movement techniques, and more high-difficulty vaults. Among the changes that have contributed greatly to the fast advancement of vaulting are the innovating movement techniques that have played an important role in replacing old techniques and creating new vaulting movements.

Research on new vaulting techniques, especially those using modern biomechanical analysis, has greatly increased the knowledge related to gymnastic vaulting theories and techniques. New technology, such as high-speed cameras, can provide accurate information that was not possible simply by observing the performance. Many new techniques have been based upon biomechanical research. However, a continuous effort has to be made to explore better techniques as competition at the world-class level has become more intense. To win a world championship in vaulting, a gymnast must apply innovative techniques and must be able to perform highly difficult vaults. A general biomechanical study is no longer sufficient for exploring new techniques. Therefore, more detailed studies are needed to determine the best way for each gymnast to coordinate body movements and to achieve the best technique potential in the execution of certain vaults.

To accomplish highly difficult vaults, a gymnast must possess not only the ability of reaching a certain speed and having enough strength, but must also have appropriate techniques during the approach run, hurdle, board takeoff, preflight, support on horse, postflight, and landing. Of the seven phases of vaulting, hurdle and board takeoff are two of the fundamental parts that play an extremely important role for the successful execution of vaults. Though a hurdle can be simply defined as taking off on one leg and landing with both feet on the board, a good hurdle technique is essential. A gymnast needs this transitional period to adjust the arms and legs used in the approach run to ensure a proper position for board takeoff that makes the best use of horizontal momentum (Hay, 1993). Also, a good board-takeoff technique is of critical importance since it involves the transition of horizontal momentum obtained during the approach run and hurdle into horizontal velocity, vertical velocity, and angular momentum required to execute different vaults. Though hurdle and board takeoff are not included in the judging of a vault during competition, they can influence the entire vault. A fast and smooth transition during the hurdle and a powerful takeoff from the board will definitely influence the preflight, support on the horse, postflight, and landing in a positive way. On the other hand, an unsmooth transition during the hurdle and a less powerful board takeoff will surely affect the whole vault in a negative way.

A review of the research literature showed that some kinematic and kinetic studies have been conducted on handspring vaults, handspring and salto-forward tucked vaults, and Tuskahara and Kasamatsu vaults (Bruggemann, 1979, 1987; Dainis, 1979, 1981; Dillman, Cheetham, & Smith, 1985; Kerwin, Harwood, & Yeadon, 1993; Kreighbaum, 1974, 1979; Ou, 1980; Takei, 1988, 1989, 1991; Takei & Kim, 1990; Tichonov, 1978). Previous studies found that (1) the horizontal velocity at board contact increased with the level of performance (Bruggemann, 1987; Takei, 1991) and (2) a large horizontal velocity and angular momentum at board takeoff were important determinants for successful performance on the vault (Bruggemann, 1987; Takei, 1989, 1991). The implication of these findings suggested that coaches should focus on the gymnasts' horizontal velocity during the hurdle and try to achieve an optimal horizontal velocity, a good angular momentum, and a greater forward-body inclination at board takeoff (Takei, 1989, 1991).

However, previous studies focused mostly on the areas that affect the final score awarded by judges. Since hurdle and board takeoff are not considered in scoring, limited research is available. First, previous studies were basically descriptive in nature with emphasis on general features. Thus, they lacked a detailed biomechanical technique analysis. Second, coaches have not benefited from the previous studies because detailed hurdle and board-takeoff technique differences between the advanced and low-skilled gymnasts were not investigated. Third, most previous studies used elite gymnasts who performed at the advanced level. In reality, most gymnastics instructors and coaches teach at the beginning and intermediate skill levels. Because hurdle and board takeoff are performed so quickly, many coaches may not realize what problems exist in young gymnasts and the proper corrections to make.

A general descriptive analysis, such as given in previous studies, obviously cannot provide detailed technical information. A complete technique analysis should include not only general information, but also specific information, such as how a gymnast's trunk, head, arms, and legs are involved; how these segments are coordinated; and what the timing is for that specific movement, as well as the interaction of body segments with the outside environment.

A review of the literature related to gymnastic vaulting theories and techniques indicated:

1. The hurdle was not included as an independent part of vaulting phases (Brown & Wardell, 1980; Bruggemann, 1979, 1987; Cooper, 1980; Cooper & Trnka, 1982; Cornelius, 1983; Dolan, 1980; Gluck, 1982; Loken & Willoughby, 1977; Murray, 1979; Puckett & Bengtson, 1979; Ryan, 1976; Schmid & Drury, 1977).

2. The hurdle was combined with either the approach run or the board-takeoff phase (Cooper, 1980; Cooper & Trnka, 1982; Cornelius, 1983; Dolan, 1980; Murray, 1979; Puckett & Bengtson, 1979; Ryan, 1976; Schmid & Drury, 1977).

3. The hurdle was listed as an independent part with either descriptive or detailed theory and technique discussion (Arnold & Stocks, 1979; Boone, 1976; Bowers, Fie, & Schmid, 1981; George, 1980; Hay, 1993; Simalevski & Gerveldovski, 1979; Tonry & Tonry, 1980).

4. The board takeoff was generally listed as an independent part with either descriptive or detailed technique discussion (Arnold & Stocks, 1979; Boone, 1976; Bowers et al., 1981; Chang, 1980; Cooper, 1980; Cooper & Trnka, 1982; Cornelius, 1983; Dolan, 1980; George, 1980; Hay, 1993; Murray, 1979; Qian, 1980; Ryan, 1976; Schmid & Drury, 1977; Simalevski & Gerveldovski, 1979; Tonry & Tonry, 1980).

Many controversial issues and techniques regarding the hurdle and board takeoff can be found in the literature. Among these are the importance of the hurdle, the hurdle distance, the proper body position during the hurdle, the proper leg movement and hand position, the proper arm-swing techniques, the appropriate board contact time, the knee flexion and extension during board contact, and torso position. Obviously, the study of hurdle and board-takeoff techniques is of significant importance for the improvement of gymnastic vaulting theory, for gymnasts' successful execution of more difficult and complex vaults, and for efficient and successful teaching and coaching.

To study the hurdle and board-takeoff techniques and to better understand the techniques being used at different skill levels, the handspring vault becomes the logical choice since it is one of the most important fundamental movements in many different vaults. The handspring vault contains crucial techniques that provide the foundation and key prerequisites for more complex and difficult vaults (Takei, 1989).

The purposes of this study were (1) to investigate in detail the technique differences between advanced and less skilled gymnasts during the hurdle step and board takeoff, (2) to detect advanced techniques in performing the hurdle and board takeoff, (3) to contribute to the improvement of vaulting theories and techniques, and (4) to provide practical recommendations for gymnastics teachers and coaches.

Research Hypotheses

For the purposes of this study, the following research hypotheses were tested:

1. The horizontal, vertical, and resultant velocity for the center of mass at selected events during the hurdle and board takeoff will differ significantly among gymnasts at different skill levels.

2. The ratio of horizontal velocity utilization for the center of mass at selected events

during the hurdle and board takeoff will differ significantly among gymnasts at different skill levels.

3. The last step length will differ significantly among gymnasts at different skill levels.

4. The hurdle distance will differ significantly among gymnasts at different skill levels.

5. The hurdle flight time will differ significantly among gymnasts at different skill levels.

6. The hurdle flight height will differ significantly among gymnasts at different skill levels.

7. The hurdle flight angle will differ significantly among gymnasts at different skill levels.

8. The time from the feet-together position to board contact will differ significantly among gymnasts at different skill levels.

9. The board contact time will differ significantly among gymnasts at different skill levels.

10. The angular displacement of the hurdle leg will differ significantly at selected events during the hurdle and board takeoff among gymnasts at different skill levels.

11. The angular displacement, angular velocity, and linear velocity of the knee joint will differ significantly at selected events during the hurdle and board takeoff among gymnasts at different skill levels.

12. The horizontal, vertical, and resultant velocity of the ankle joint will differ

significantly at selected events during the hurdle and board takeoff among gymnasts at different skill levels.

13. The angular displacement of the hip joint will differ significantly at selected events during the hurdle and board takeoff among gymnasts at different skill levels.

14. The angular displacement and angular velocity of the shoulder joint will differ significantly at selected events during the hurdle and board takeoff among gymnasts at different skill levels.

15. The angular displacement of the trunk will differ significantly at selected events during the hurdle and board takeoff among gymnasts at different skill levels.

16. The horizontal, vertical, and resultant velocity of the wrists will differ significantly at selected events during the hurdle and board takeoff among gymnasts at different skill levels.

17. The angular and linear movement coordination of the body segments will differ significantly from the feet-together position to board contact, from the board contact to board takeoff, and at the instant of board takeoff among gymnasts at different skill levels.

18. The angular velocity of the body at board takeoff will differ significantly among gymnasts at different skill levels.

19. The arm-movement patterns will differ significantly during the hurdle and board takeoff among gymnasts at different skill levels.

Operational Definitions

For the purposes of this study, the following events and variables were defined:

Events

Board contact--the instant depicted in the frame in which the vaulter's feet were first seen to have contacted the board.

Board takeoff--the instant depicted in the frame in which the vaulter's feet were first seen to have broken contact with the springboard.

Feet together--the instant depicted in the frame in which the vaulter's feet were first seen together before board contact.

Hurdle foot takeoff--the instant depicted in the frame in which the vaulter's hurdle foot was first seen to have broken contact with the floor.

Hurdle foot touchdown--the instant depicted in the frame in which the vaulter's foot was first seen to have contacted the floor.

Last step takeoff--the instant depicted in the frame in which the vaulter's foot was first seen to have broken contact with the floor.

Variables

Angular displacement of the hip joint at the feet- together position, board contact, and board takeoff--the average angle of left and right hips by the connection of the shoulder-hip-knee at the instant of the feet-together position, board contact, and board takeoff.

Angular displacement of the hip joint on the side of the free leg at the hurdle foot takeoff--the hip-joint angle by the connection of the shoulder-hip-knee on the free-leg side at the instant of hurdle foot takeoff.

Angular displacement of the hip joint on the side of the hurdle push-off leg at the hurdle foot takeoff--the hip-joint angle by the connection of the shoulder-hip-knee at the instant of hurdle foot takeoff.

Angular displacement of the hurdle push-off leg at the hurdle foot takeoff--the angle calculated from the connection of hip-ankle with the horizontal direction at the instant of hurdle foot takeoff.

Angular displacement of the knee joint at the feet-together position, board contact, and board takeoff--the angle from the connection of hip-knee-ankle line at the first frame of seeing the feet-together position, board contact, and board takeoff.

Angular displacement of the legs at the feet-together position, board contact, and board takeoff--the average angle calculated from the connection of hip-ankle on both legs with the horizontal direction at the instant of the feet-together position, board contact, and board takeoff.

Angular displacement of the shoulder joint at the feet-together position, board contact, and board takeoff--the average angle calculated from the connection of elbow-shoulder-hip on both sides at the instant of the feet-together position, board contact, and board takeoff.

Angular displacement of the trunk at the hurdle foot takeoff, feet-together position, board contact, and board takeoff--the average angle calculated from the connection of the shoulder-hip on both sides with the vertical direction at the instant of hurdle foot takeoff, feet-together position, board contact, and board takeoff.

Angular velocity of the body at the board takeoff--the average angular velocity of the body calculated from the connection of the shoulder-ankle line on both sides at the instant of board takeoff.

Angular velocity of the shoulder joint at the maximum value, feet-together position, board contact, and board takeoff--the average angular velocity calculated from both shoulders at the instant of maximum value, feet-together position, board contact, and board takeoff.

Board contact time--the period from the first frame of board contact to the last frame of board contact before board takeoff.

Horizontal, vertical, and resultant velocities of the wrists at the maximum value, feet-together position, board contact, and board takeoff--the average horizontal, vertical, and resultant velocities of both wrists at the maximum value, feet-together position, board contact, and board takeoff.

Hurdle flight angle--the angle between the direction of the center of mass movement from the last frame before the hurdle foot takeoff to the instant of hurdle foot takeoff and the horizontal direction.

Hurdle flight height--the vertical distance from the highest point of the center of mass during the hurdle minus the vertical displacement of the center of mass at the last frame before hurdle foot takeoff.

Hurdle flight time--the period from the instant of hurdle foot takeoff to the instant of board contact.

Hurdle length--the horizontal distance from the toes at the instant of hurdle foot touchdown to the toes at the instant of board contact.

Knee flexion during board contact--the angular displacement of the knee joint at board contact minus the minimum angular displacement of the knee joint during board contact.

Last step length--the horizontal distance from the toes in the last frame before the last step takeoff to the toes at the instant of hurdle foot touchdown.

Maximum angular velocity of the hurdle push-off leg at the knee joint--the maximum angular velocity found during the hurdle period.

Minimum angular displacement of the hurdle push-off leg at the knee joint during the hurdle--the angle from the connection of hip-knee-ankle line at the instant of minimum value during the hurdle.

Ratios of horizontal velocity utilization at the hurdle foot takeoff, feet-together position, board contact, and board takeoff--the values calculated by dividing the center of mass horizontal velocity at the hurdle foot takeoff, feet-together position, board contact, and board takeoff with the horizontal velocity at the hurdle foot touchdown.

Time from the feet-together position to board contact--the period from the first frame of the feet-together position to the last frame before board contact.

Basic Assumptions and Limitations

This study was based on the following assumptions:

1. The subjects reported accurate data about their age, sex, years of practice experience, and their skill level.

2. The performance of subjects was normal during the video recording.

3. The video cameras were valid and reliable instruments for measuring the gymnasts' kinematic features.

4. The two cameras were synchronized.

5. The computer-assisted digitizing and calculation software systems were valid for data analysis.

Some limitations were expected in this study. First, the number of subjects was limited, and they were all from the United States. The study results may not fully represent vaulters all over the world. Second, the comprehensive biomechanical study on the hurdle and board takeoff should include the dynamic analysis to investigate the interaction between a vaulter and the springboard, as well as kinematic observation. The results from this study were limited by kinematic data obtained by two synchronized video cameras without force detectors connected under the springboard.

Significance of the Study

The significance of the study included the following:

1. The three-dimensional study of the hurdle and board-takeoff techniques will provide many detailed kinematic and technical features that exist among different skill-level groups, which will increase the understanding about the hurdle and board-takeoff techniques used at different skill levels.

2. It will open a new direction for biomechanical analysis by emphasizing the relative movement and the coordination of body segments. Not only will the center of mass movement be analyzed as traditional studies do, but the relative movement of the trunk,

arms. and legs also will be emphasized in this study.

3. Gymnastics teachers and coaches will have a better understanding of the advanced hurdle and board-takeoff techniques.

4. The study will make a significant contribution to the improvement of gymnastic vaulting theory.

5. The results can be applied by gymnastics teachers and coaches for more efficient and successful coaching.

CHAPTER 2

Review of Related Literature

In this study, the review of literature related to the hurdle and board takeoff is organized into the following parts: (1) literature related to hurdle theories and techniques; (2) literature related to board-takeoff theories and techniques; (3) literature related to studies on the hurdle; (4) literature related to studies on the board takeoff; and (5) summary of literature review.

Literature Related to Hurdle Theories and Techniques

Since the birth of modern gymnastics, many gymnastics teaching and coaching books have discussed vaulting theories and techniques. However, because of the fast development of new vaulting movements and techniques in recent years, many old vaulting techniques have become obsolete. Therefore, this study restricted the review of related literature to those that have included a discussion of vaulting theories and techniques within the last 20 years.

The review of literature related to gymnastic vaulting theories and techniques indicated the following:

1. The hurdle was not considered an important part of vaulting and was not listed as a separate part of vaulting movements by some authors (Brown & Wardell, 1980; Bruggemann, 1987; Cooper, 1980; Cooper & Trnka, 1982; Cornelius, 1983; Dolan, 1980; Gluck, 1982; Loken & Willoughby, 1977; Murray, 1979; Puckett & Bengtson, 1979; Ryan, 1976; Schmid & Drury, 1977).

2. The hurdle was put into either the approach-run or board-takeoff phase (Cooper. 1980: Cooper & Trnka. 1982: Cornelius. 1983: Dolan. 1980: Murray. 1979: Puckett & Bengtson. 1979; Ryan. 1976: Schmid & Drury. 1977).

3. The hurdle was listed as an independent part of vaulting movements with either general or detailed theory and technique discussion (Arnold & Stocks. 1979: Boone. 1976: Bowers et al.. 1981: George. 1980: Hay. 1993: Simalevski & Gerveldovski. 1979: Tonry & Tonry. 1980). Apparently. different opinions about the hurdle in the structure of vault movement. as well as its importance. have existed among coaches and scholars.

Regarding the distance of hurdle flight. there is a lack of agreement about the distance of the hurdle. Some authors believe that the hurdle trajectory should be long (Murray. 1979: Cooper. 1980). They considered the short hurdle a common error for bad vaulters. However. some authors believe that a good hurdle should be short in distance (Arnold & Stocks. 1979: Bowers et al.. 1981: Cornelius. 1983: George. 1980: Tonry & Tonry. 1980). Others believe that the hurdle distance is not an important issue. Gymnasts should treat the hurdle as a continuation of the run by getting both feet to the board at the same time. Without breaking strides. the gymnast should run into the board instead of jumping onto the board (Dolan. 1980: Ryan. 1976: Schmid & Drury. 1977). In the gymnastics textbook of the former Soviet Union (Simalevski & Gerveldovski. 1979). the average hurdle distance was from 2.3 to 2.8 meters.

The trajectory of the hurdle is an important part of hurdle theory. The consensus on this issue is that the hurdle should be low and fast to keep the horizontal speed loss to a minimum (Arnold & Stocks. 1979: Boone. 1976: Bowers. et al.. 1981: Cornelius. 1983:

George. 1980; Cooper. 1980; Dolan. 1980; Murray. 1979; Ryan. 1976; Schmid & Drury. 1977; Tonry & Tonry. 1980). The gymnastics textbook of the former Soviet Union (Simalevski & Gerveldovski. 1979) offers two specific targets for a proper hurdle trajectory: (1) the body-takeoff angle at the hurdle foot takeoff should be between six and nine degrees with the horizontal direction and (2) the body's center of mass should rise 15 to 25 centimeters in height during the hurdle.

The body position during the hurdle is another controversial problem that has not been solved. Some authors believe that the hurdle step imparts backward momentum to the gymnast's body that causes the body position to be in a slight backward-leaning position during the hurdle (Arnold & Stocks. 1979; Hay. 1993). Many authors believe that during the hurdle the gymnast should make a constant effort not to lean forward at board contact and. in addition. the gymnast should keep a vertical or a slight backward-leaning body angle to create a proper blocking action at board takeoff (Arnold & Stocks. 1979; Dolan. 1980; George. 1980; Hay. 1993; Murray. 1979; Ryan. 1976; Schmid & Drury. 1977; Tonry & Tonry. 1980). However. a different view can be found in the college gymnastics textbook of the former Soviet Union (Simalevski & Gerveldovski. 1979). These authors believe that. at the moment of hurdle feet contact with the board. the gymnast should keep the body leaning forward at an angle of between 5 and 26 degrees.

The movement of the legs during the hurdle is an important part of hurdle techniques since they can have a significant impact on the board takeoff. There is a consensus on the blocking action of the legs that at the end of the hurdle both feet should be placed in front of the center of mass to produce a proper amount of vertical momentum needed for the execution of vaulting movements (Arnold & Stocks, 1979; Boone, 1976; Bowers et al., 1981; Chang, 1980; Hay, 1993; George, 1980; Cooper, 1980; Murray, 1979; Schmid & Drury, 1977; Simalevski & Gerveldovski, 1979; Tonry & Tonry, 1980). Some authors added body rotation after the blocking action as another function for the movement of hurdle legs (Bowers et al., 1981; George, 1980; Hay, 1993; Murray, 1979). However, there is disagreement on how to reach the blocking position. Some authors believe that the blocking position should be done by the slight backward rotation of the body during the hurdle (Arnold & Stocks, 1979; Bowers et al., 1981; George, 1980; Hay, 1993). Others believe that the feet-blocking position should be executed by continuous sprinting and quickly bringing feet in front of the center of mass (Chang, 1980; Cooper, 1980; Dolan, 1980; Murray, 1979; Ryan, 1976; Schmid & Drury, 1977; Simalevski & Gerveldovski, 1979; Tonry & Tonry, 1980).

Concerning other leg-movement techniques, Bowers et al. (1981) and George (1980) pointed out that the angles of the block should be based on the speed of sprinting, the gymnast's ability to perform the blocking action, and the need for vertical lifting and body angular momentum for the specific vaulting movement. Simalevski and Gerveldovski (1979) emphasized that the powerful takeoff by the hurdle push-off leg was extremely important for a successful hurdle. Cooper (1980) stated that the front-leg knee lift should be low to allow both legs to come together quickly. Schmid and Drury (1977) pointed out that the hurdle legs should be extended forward before board contact. Tonry and Tonry (1980) realized the complexity of the hurdle and stated that a good hurdle requires careful coordination between arms and legs.

During the hurdle period, the upper body and legs, as well as the arms, are actively involved. However, there seems to be no agreement on the importance of the arms and technical details, such as how both arms should be coordinated, which kind of arm movement should be involved, which is the advanced arm-swing technique, and what kind of arm movement should be considered a less advanced technique. Hay (1993) stated that the gymnast should lower both arms before the hurdle. After body takeoff, the arms should be swung in a forward-and-upward direction. Then the gymnast should bring both hands behind the body to prepare for the vigorous forward-and-upward swing of the arms at board takeoff. According to this description, the motion of the arms seems like a side-circling swing style.

Dolan (1980) believes that, just before stepping into the hurdle, the gymnast should swing the arms back and down to prepare for board takeoff. A little difference can be found in the works of Cooper (1980) and Tonry and Tonry (1980), which pointed out that the gymnast should hold his or her arms behind the hips during the hurdle. The gymnastics textbook of the former Soviet Union (Simalevski & Gerveldovski, 1979) requires that the gymnast should keep the arms on the sides at the moment of board contact. According to the illustration in George's (1980) work, the hands should be placed above the head at board contact. Obviously, no consensus has been reached on where the arms should be placed at either hurdle foot takeoff or board contact.

As for the styles of the arm swing, there are a few authors who reported different arm-swing techniques. In Tonry and Tonry's (1980) book, the swing of the arms was organized into two categories. One category is called "hurdle with basic arm lift" (Tonry &

Tonry, 1980, p. 17). This type of arm movement was defined as placing the arms next to the hips as the gymnast jumps from one foot to two feet and lifting the arms forward and upward before board takeoff (Tonry & Tonry, 1980). Another type of arm movement is called "hurdle with circling arm lift" (Tonry & Tonry, 1980, p. 19). The second type of arm-moving technique was explained as moving the arms sideways-upward as the hurdle starts. Then, as the feet come together, the gymnast's arms complete the circle and move forward-upward before board takeoff (Tonry & Tonry, 1980). The authors did not state which arm-swing style was more advantageous than the other or which style should be adopted by gymnasts.

Chang (1980) classified the arm-swing into three types. The first type of arm-swing technique should be performed beginning with the hands behind the hips, followed by having both arms swing forward and upward, and ending with the hands in front of the head. The second type of arm-swing technique was described as the hands reaching forward, followed with the natural sprinting posture onto the board. The third type of arm-swing style was described as both arms being swung in an upward position, then reaching forward at board takeoff. Chang (1980) reported that the most advanced male gymnasts in China use the first type of arm-swing technique. Qian (1980) listed two types of arm-swing techniques during the hurdle and board takeoff. One type was both arms swinging together, while the other type was keeping the natural sprinting posture with one arm in front of the body and the other arm behind the body and then both hands reaching forward. Qian (1980) believes that the second type of arm-swing technique had an advantage in avoiding horizontal velocity loss during the hurdle and board takeoff.

In some authors' works, the arm-movement technique during the hurdle is not mentioned in the discussion of hurdle theories and techniques (Arnold & Stocks, 1979; Boone, 1976; Cornelius, 1983; Dolan, 1980; Murray, 1979; Ryan, 1976; Schmid & Drury, 1977).

By reviewing the literature related to hurdle theories and techniques, many controversial issues can be found, such as the importance of the hurdle in the structure of general vaulting components, hurdle distance, proper body position during the hurdle, leg-movement techniques, hand position, and arm-swing styles. In addition, there are still some unanswered technique details, such as how the hurdle push-off leg should be moved, what is the appropriate timing for placing the feet together, how both legs should be moved before contacting the springboard, how both arms should be coordinated for the nature-sprinting style of arm movement, how the hands should be moved at board takeoff, how the torso should be moved to keep the horizontal velocity loss at a minimum, and what kind of body position an advanced vaulter should have at board takeoff.

Literature Related to Board Takeoff Theories and Techniques

The importance of board takeoff is well recognized. A reviewing of gymnastic vaulting theories and techniques of the last 20 years indicated that the board takeoff has always been listed as a separate part, though some authors put the hurdle in the board-takeoff phase (Arnold & Stocks, 1979; Boone, 1976; Bowers et al., 1981; Chang, 1980; Cooper, 1980; Cooper & Trnka, 1982; Cornelius, 1983; Dolan, 1980; George, 1980; Hay, 1993; Murray, 1979; Qian, 1980; Ryan, 1976; Schmid & Drury, 1977; Simalevski & Gerveldovski, 1979; Tonry & Tonry, 1980). However, some difference can be found in the function of the board takeoff. Some authors believe that the board takeoff should provide the gymnast with a horizontal momentum, vertical lifting, and angular momentum necessary for the vault being performed (Arnold & Stocks, 1979; Boone, 1976; George, 1980; Hay, 1993). There are some authors who believe that the board takeoff should focus on how to convert the horizontal momentum into a good vertical lift (Bowers et al., 1981; Cooper, 1980; Dolan, 1980; Murray, 1979; Ryan, 1976; Schmid & Drury, 1977).

The board takeoff is usually considered a powerful blocking action that requires extensive leg-muscle movement. Many authors believe that the force of impact on the board causes the hip, knee, and ankle joints to undergo slight flexion before the forceful extension of those joints occurs (Arnold & Stocks, 1979; Bowers et al., 1981; Cooper, 1980; Dolan, 1980; George, 1980; Schmid & Drury, 1977; Simalevski & Gerveldovski, 1979). However, Murray (1979) stated that "as soon as the feet touch the board the extension must occur quickly; there is no pause" (p. 119). Apparently, he believes that there should be no knee flexion during board-takeoff phase.

It is generally believed that the board-takeoff action should be quick and powerful (Arnold & Stocks, 1979; Bowers et al., 1981; Cooper, 1980; Dolan, 1980; George, 1980; Murray, 1979; Schmid & Drury, 1977; Simalevski & Gerveldovski, 1979; Tonry & Tonry, 1980) in order to maintain proper horizontal velocity, proper vertical lifting, and necessary angular momentum. However, a different opinion can be found in Boone's (1976) work. He stated that a slight backward lean of the body at board contact will increase the time on the springboard. This increased time on the board will result in an increased vertical velocity at board takeoff. In other words, the increased body-forward lean at board takeoff will reduce the time on the board. As a result, the gymnast's vertical velocity will decrease accordingly.

In regard to the torso position during board takeoff, controversial theories and techniques can be found in gymnastics teaching and coaching books. Dolan (1980) stated that the body position is directly related to the vertical lift. If a gymnast leans forward, the vertical flight will be low; and, vice versa, if a gymnast keeps the torso in a vertical or backward-leaning position, the vertical lift will be higher. Bowers et al. (1981) believe that the posture of the torso should be straight during board takeoff. Any sharp bend in the trunk or at the hip joint will lower the height of the center of mass, which will result in greater effort to achieve the vertical lift needed, as well as longer time for the body to get a good stretch position for the preflight onto the horse. Murray (1979) stated that "the correct body position on the board is a slight back lean in which the body forms less than a 90-degree angle with the board" (p. 119). George (1980) believes that the proper body position should be standing as tall as is mechanically possible during board contact. In this way it will maximize the height of the gymnast's center of mass and thus will increase the possible vertical lift from the board. According to Simalevski and Gerveldovski (1979), the correct torso position at board contact should be a slight lean forward. Obviously, the disagreement on the correct torso position during board contact and board takeoff among the scholars has not been solved.

It is a common belief that the hips, knees, ankles, and even toes should be quickly extended soon after the board contact. However, the techniques on how the arms should be coordinated with the knee extension have not been consistent. Dolan (1980) pointed out that, as the board takeoff starts, the gymnast should swing his or her arms up and forward to shoulder level. Bowers et al. (1981) stated that most vaulters should raise their arms to just above head level, with elbows thrust up to forehead level. Cooper (1980) pointed out that, as feet start contacting the board, the arms should reach forward and upward to help the vertical lift.

Schmid and Drury (1977) stated that the use of the arms during the hurdle and board takeoff can be different based on performers. They suggested that during the takeoff the gymnast should quickly bring the arms forward to shoulder level. George (1980) stated that during board takeoff the arms should finish the upward throw action with arms above the head. In the gymnastics textbook of the Former Soviet Union (Simalevski & Gerveldovski, 1979), the arm-swing action was considered very important for the takeoff of the legs from the board. The correct arm swing can increase the height of body takeoff from the board by 20 to 25 percent. The arm swing should stop at head level and according to the takeoff of the legs from the board. Apparently, no agreement has been reached on how to start the arm swing, what the swing direction should be, and where to stop the arm swing during board takeoff.

The review of the board-takeoff theories and techniques shows that many controversial issues and confusing techniques have existed among the authors. The blocking action during board takeoff, which converts horizontal momentum into a vertical lift, has been widely emphasized in the past literature. However, no agreement has been reached on the function of board takeoff, knee flexion and extension during board takeoff, board contact time, appropriate torso position during board takeoff, hip angular displacement during board takeoff, correct position of the hands at board contact and board takeoff, and correct arm-swing techniques.

Literature Related to Studies on the Hurdle

Dillman et al. (1985) conducted a two-dimensional descriptive biomechanical analysis on the 1984 men's Olympic long-horse vaulting. The eight male finalists were filmed at 100 frames per second during the competition. This study found that the time of the hurdle for the handspring group vaults was 0.23 second. The same duration was found on the Tuskahara vaults. The length of the hurdle for handspring and Tuskahara vaults was 2.45 and 2.29 meters, respectively. The angular position of the body at body takeoff was 83.25 degrees for handspring vaults and 90 degrees for Tuskahara vaults. No detailed technique analysis was offered in this study.

Takei (1989) conducted a study on handspring vaults. Forty elite male gymnasts were selected in the 1987 Pan American Games. A 16-mm motion-picture camera was used, with the frame rate at 101 frames per second. The average time of the hurdle was reported at 0.24 second. The horizontal velocity of the center of mass at body takeoff was calculated at 7.50 meters per second.

In 1990, Takei and Kim studied the handspring and salto-forward tucked vaults at the 1988 Olympic Games. The subjects included 51 male gymnasts participating in the 1988 Olympic Games. A 16-mm high-speed camera filming at the rate of 100 Hz was used to record the performance of the subjects. The study found that the average horizontal velocity of the 51 gymnasts at the body takeoff was 7.93 meters per second. In comparison, the average horizontal velocity of the 41 male gymnasts participating in the 1986 USA Gymnastics Championships was 7.20 meters per second at the body takeoff.

Takei (1991) conducted a comparison study regarding the techniques used in performing the handspring and salto- forward tucked vaults at the 1988 Olympic Games. Though the hurdle techniques were not analyzed in this study, he recommended that gymnasts should have a fast horizontal velocity in the hurdle.

Kerwin et al. (1993) studied hands-placement techniques in performing Tuskahara and Kasamatsu long-horse vaulting. Seventeen elite male gymnasts competing in the 1991 World Student Games at Sheffield, UK, were selected and filmed with two cameras running at 50 Hz for a 3-D analysis. They reported the average horizontal velocities during the hurdle were 7.75 and 8.05 meters per second for the two different groups using different hand-placement techniques.

Ou (1980) conducted a study on the techniques of handspring and salto-forward vaults. Five subjects were selected from the Chinese National Gymnastics Teams and filmed with a high-speed camera operating at 50 Hz per second. He reported that the average horizontal velocity for the five elite Chinese gymnasts was at 6.30 meters per second and the average resultant velocity was at 7.10 meters per second during the hurdle.

By reviewing the previous biomechanical studies related to the handspring and Tuskahara vaults (Bruggemann, 1979, 1987; Dainis, 1979; Dillman et al., 1985; Kerwin et al., 1993; Kreighbaum, 1974, 1979; Nelson, Gross, & Street, 1985; Ou, 1980; Takei, 1988, 1989, 1991; Takei & Kim, 1990; Tichonov, 1978), the following points can be found:

1. Hurdle-technique analysis was not included in some of the biomechanical studies

(Bruggemann, 1979, 1987; Dainis, 1979, 1981; Kreighbaum, 1974, 1979; Nelson et al., 1985; Takei, 1988, 1991; Tichonov, 1978). Some studies started the analysis from board takeoff or even later. The hurdle step apparently was not considered an important component in the vaulting sequences.

2. Some of the studies only touched upon the general features of hurdle step and put the focus on the areas that affect the final score given by the judges, such as preflight, horse contact and takeoff, postflight, and landing (Dillman et al., 1985; Kerwin et al., 1993; Ou, 1980; Takei, 1989; Takei & Kim, 1990).

3. No studies have focused on the area of hurdle techniques. Therefore, very little information is available about detailed studies on hurdle techniques.

Literature Related to Studies on Board Takeoff

More studies have been conducted on the board takeoff than on the hurdle step. Bruggemann (1987) conducted a study on biomechanics in gymnastics that included a study on vaults. He made these main points:

1. The magnitude of changes in the vertical and angular momentum during board takeoff is related to the level of performance. In other words, the higher the skill level, the greater the vertical velocity and angular momentum that will take place at board takeoff.

2. No significant difference was found on the time of board contact among different skill-level groups. However, the average horizontal and vertical ground reaction forces increase with the level of performance.

3. There is a significant difference in angular momentum at takeoff among different skill-level groups.

In this study, Bruggemann (1987) also revealed some results of his previous study. He reported that the time of board contact was 0.11 second for world class and 0.10 second for both national and junior class. At board takeoff, body position was 74.3 degrees for world class, 75.9 degrees for national class, and 79.7 degrees for junior class. The horizontal velocity at board contact was 7.98 meters per second for world class, 7.40 meters per second for national class, and 6.79 meters per second for junior class. At board takeoff, the horizontal velocity was 5.17 meters per second for world class, 5.24 meters per second for national class, and 4.70 meters per second for junior class. The vertical velocity at board takeoff was 4.52 meters per second for world class, 4.31 meters per second for national class, and 3.88 meters per second for junior class. The angular velocity at board takeoff was 398.6 degrees per second for world class, 358.1 degrees per second for national class, and 339.8 degrees per second for junior class.

Dillman et al. (1985) reported the following:

1. The average time on the board was 0.11 second for Olympic gymnasts.

2. The body position at board takeoff was 74.9 degrees on average.

3. The average horizontal velocity at board contact was 7.79 meters per second, and the average vertical velocity at board takeoff was 4.49 meters per second.

4. The body angular positions for handspring vaults were 117.50 degrees at board contact and 74.88 degrees at board takeoff.

5. The body angular positions for Tuskahara vaults were 117.5 degrees at board contact and 76.13 degrees at board takeoff.

6. The horizontal velocities for handspring vaults were 7.79 meters per second at

board contact and 5.11 meters per second at board takeoff.

7. The horizontal velocities for Tuskahara vaults were 7.71 meters per second at board contact and 5.21 meters per second at board takeoff.

8. The vertical velocities at board takeoff for handspring vaults and Tuskahara vaults were 4.49 meters per second and 4.42 meters per second, respectively.

In 1974, Kreighbaum studied the mechanics of the use of a Reuther board during side-horse vaulting. Eight female vaulters from the 1972 Northwest District Gymnastic Meet were selected in this study. Each subject was filmed with a 16-mm camera at 180 frames per second from the hurdle step to preflight. A special Reuther board to which eight strain gauges were attached and deflections in the board were recorded by means of a light tracing on photosensitive paper was used in this study. The study found the following:

1. The maximal forces were 2,160 to 1,180 pounds, and the submaximal forces were 1,050 to 550 pounds.

2. The magnitude of the maximal deflection on the board indicated no significant correlation with the amount of the submaximal deflection.

3. The maximal deflection registered a significant correlation with the weight of the vaulter.

4. The submaximal deflection did not suggest a significant correlation with the weight of the vaulter.

5. The vaulter reached her maximal downward displacement at the point of the maximal board deflection, followed by decreased board deflection, while the balls of the feet continued their rolling, and the hip, knee, and ankle joints extend simultaneously with the

submaximal deflection.

Kreighbaum (1974) believes that arm contribution to board defection can be neglible. Consequently, the arm segments, which include hand, forearm, and upper arm segments, were omitted from this study. If the vaulter prefers to hold her arms at her side during the hurdle, she should try to accelerate the arms prior to the extension of the trunk. In this way, the arm action will not increase the vertical forces downward on the trunk at the time when the trunk is attempting to accelerate upward.

Finally, Kreighbaum (1974) summed up his study with the following points:

1. Two deflections occurred on the board with a partial unweighting between deflections during board takeoff.

2. The total impulse on the board did not indicate the contribution of the board to the takeoff.

3. The acceleration and deceleration of segment sequences during board takeoff should start from the top segment downward, with the deflection of the board occurring at maximal deceleration of the last segment.

In 1979, Kreighbaum conducted another study on qualitative descriptions of the lower leg and board movement in vaulting. One male and one female national-level vaulter were filmed during handspring vaults. The camera was set at 400 frames per second, and the films were observed with a projector. The study found that the deflection pattern of a rear-foot placement was started from the heel portion, followed by the depression of the toe portion, then the depression of the whole foot, a slight unweighting of the toe portion, an unweighting of the middle portion followed by another depression period of the entire board.

and finally a total unweighting of the board at takeoff. However. the pattern in which the contact point is in the middle of the board is less complicated. Usually. the initial contact and depression of the board start first. followed by either a slight unweighting or static holding period. and finally the unweighting at board takeoff. The author suggested that the best landing place on the board should be in the middle between front and back springs.

Nelson et al. (1985) conducted a study on female Olympic gymnasts during the women's vaulting events of the 1984 Los Angeles Olympic Games. Eight individual vault finalists were filmed with cameras operated at 100 frames per second. The study reported that the average board-contact time for the six gymnasts using handspring or Tuskahara vaults was 0.11 second. The average horizontal velocity on board contact was 6.9 meters per second. At board takeoff. the average horizontal velocity was 4.9 meters per second. and the mean vertical velocity was 3.7 meters per second.

According to Ou's (1980) study on handspring and salto-forwards.

1. The blocking angle of the five Chinese National Gymnastics Team male gymnasts was 60 degrees from the vertical line at board contact.

2. The average hip angle at board contact was 124 degrees.

3. The mean torso-forward inclination angle was 26 degrees at board touchdown.

4. The average board contact time was 0.10 second.

5. The average takeoff angle was 88 degrees.

6. The average horizontal velocity at board takeoff was 5.0 meters per second.

7. The mean vertical velocity at board takeoff was 4.56 meters per second.

He also reported that the knee and ankle joints went through a passive flexion before forceful extension. Ou also stated that the arm swing and trunk extension should be continuous during the board contact period. At the end of the board takeoff, the arms should be swung to head level or a little higher.

Takei (1988) conducted a study on the techniques used in performing handspring and salto-forward tucked vaults. The subjects included 41 all-around male gymnasts participating in the 1986 USA Gymnastics Championships. A 16-mm motion-picture camera, operating at the rate of 101 frames per second, was used in this study. He reported:

1. The mean horizontal velocities were 7.33 meters per second at board touchdown and 5.02 meters per second at board takeoff.

2. The average vertical velocity at board takeoff was 3.69 meters per second.

3. The average time on the board was 0.13 second.

Takei (1988) concluded that the horizontal velocity at board takeoff is an important factor for successful performance. He also recommended that coaches should focus on developing a fast horizontal velocity at board takeoff.

In Takei's (1989) study, the average horizontal velocity for the 40 elite male gymnasts performing a handspring vault during the 1987 Pan American Games was 7.50 meters per second at board contact and 5.19 meters per second at board takeoff. The average vertical velocity at board takeoff was 3.68 meters per second, and the average time on the board was reported at 0.134 second. He also revealed that the horizontal velocity, as well as time of postflight, had the highest correlation coefficient with the judges' score ($r = 0.50$). Based on this study, Takei recommended that coaches should focus on achieving a fast horizontal velocity, a large angular momentum, and a greater forward-body inclination at board takeoff.

Takei and Kim (1990) reported:

1. The average horizontal velocities for 51 male gymnasts participating in the 1988 Olympic Games were 7.93 meters per second at board contact and 5.31 meters per second at board takeoff.

2. The mean vertical velocity at board takeoff was 3.76 meters per second.

3. The mean time on the board was 0.136 second.

4. The body-inclination angles at board contact and at board takeoff were 123.4 degrees and 75.6 degrees, respectively, for the 1988 Olympic gymnasts. In comparison, the 1986 USA Gymnastics Championships gymnasts had 121.6 degrees at board contact and 78.3 degrees at board takeoff.

5. The vertical forces exerted on the Olympic gymnasts during board contact were 4.9 times the body weight.

Finally, the authors concluded that, compared with the 1986 USA Gymnastics Championships gymnasts, the Olympic gymnasts had much greater horizontal velocity at board contact, had longer time on the board and greater reduction of the horizontal velocity during board contact, and took off from the board with quicker horizontal velocity.

Even among the 1988 Olympic gymnasts, some kinematic difference can be found in the study of Takei (1991). He compared the 11 highest scored vaults of the 51 Olympic gymnasts, with the 11 lowest scored vaults at selected instants. The study revealed:

1. The mean horizontal velocity at board contact was 8.19 meters per second for high-score vaults and 7.69 meters per second for low-score vaults.

2. The average vertical velocity at board takeoff was 5.52 meters per second for

high-score vaults and 5.08 meters per second for low-score vaults. Takei concluded that the better gymnasts had faster horizontal velocity at board contact and departed from the board with quicker horizontal and vertical velocity than the low-scored gymnasts.

The review of the previous studies related to the board takeoff on vaulting indicated:

1. The focus has been on the general features, such as the center of mass horizontal velocity and vertical velocity at board contact and board takeoff, the body position at board contact and board takeoff, and the board contact time.

2. Two kinetic studies have been conducted in regard to the interaction between movement sequences of body segment and board deflection, as well as its relationship with foot placement (Kreighbaum, 1974, 1979).

3. Some kinetic data, such as the impulses on the board, were based on the calculation of kinematic data (Takei, 1988, 1989, 1991; Takei & Kim, 1990).

Meanwhile, some contradictory findings can be found on board contact time (Bruggemann, 1987; Takei & Kim, 1990), vertical forces on the board during the takeoff (Kreighbaum, 1974; Takei, 1988, 1989, 1991; Takei & Kim, 1990), and the coordination of body segments during board takeoff (Kreighbaum, 1974; Ou, 1980).

In addition, there are still some unanswered questions regarding board-takeoff features and techniques, such as the angular displacement of the knee joint during the board contact period among different skill-level gymnasts, the coordination among the knees, hip, and shoulder joints during board takeoff at the different skill levels, the relationship between the arm swing and the horizontal, vertical, resultant, and angular velocities at the center of mass, and the relationship between the different blocking techniques of lower legs and the board-takeoff velocities. Obviously, further studies are needed to understand the board-takeoff techniques better and to increase our knowledge of gymnastics vaulting.

Summary of Literature Review

The review of literature related to the hurdle and board-takeoff theories, techniques, and studies has clearly indicated that the available study results have been very limited and there are still many controversial issues yet to be answered. Though some studies have been conducted on the hurdle and board takeoff (Bruggemann, 1979, 1987; Dainis, 1979, 1981; Dillman et al., 1985; Kerwin et al., 1993; Nelson et al., 1985; Ou, 1980; Takei, 1988, 1989, 1991; Takei & Kim, 1990; Tichonov, 1978), only some general features can be found from these studies, such as the center of mass horizontal and vertical velocity at board contact and board takeoff, body position, board contact time, and body angular velocity. Most of the studies were designed to focus on the areas, such as preflight, takeoff from the horse, postflight, and landing, that affect the final scoring by the judges. In comparison, the kinematic studies that focused on the hurdle and board takeoff have been very limited.

The only two studies specifically on the board contact and board takeoff by Kreighbaum in 1974 and 1979 have also turned out to be less comprehensive. First, the subjects in his studies were very limited, and second, his study results were also very limited. One of his studies related to the interaction between vaulters and the Reuther board was carried out without consideration of arm segments. His other study, which had only two subjects, was focused only on lower leg and board movement.

The limited studies on the hurdle and board takeoff, along with some contradictory findings, apparently cannot give many answers to the controversial issues and techniques discussed in the gymnastics teaching and coaching books. Obviously, further studies are necessary to provide the advanced and detailed hurdle and board-takeoff techniques that gymnastics teachers and coaches want to study.

CHAPTER 3

Methods

Subjects

This study was approved by the Middle Tennessee State University Human Subject Committee (see Appendix A). A total of 40 male and female gymnasts were selected from the following three private gymnastics clubs and one university gymnastics team: Cedars Gymnastics in Murfreesboro, Tennessee; Franklin Gymnastics School in Franklin, Tennessee; Knoxville Gymnastics Training Center in Knoxville, Tennessee; and Ohio State University. All subjects signed the Informed Consent Form (see Appendix B). Among the 40 gymnasts, 14 male gymnasts were at the beginning skill level (Begin.), 7 male gymnasts were at the intermediate skill level (InterM.), 6 male gymnasts were at the advanced skill level (Advan.), and 13 female gymnasts were at the intermediate skill level (InterF.). The criteria for selecting the advanced male gymnasts were that they were on the National Gymnastics Teams or were finalists in the vaulting event during the national-level competition and had at least eight years of training experience in gymnastics. The standard for selecting the intermediate skill-level male and female gymnasts was that they had at least four years of training experience in gymnastics and participated in the regional or national optional-level competition on vaults. The gauge for selecting beginning skill-level male gymnasts was that they had less than three years of training experience and practiced the handspring vault on the side horse. In this study, some of the beginning skill-level gymnasts were spotted before supporting on the horse since they could not perform the handspring vault by themselves.

A pilot study was conducted on one advanced male gymnast and five intermediate female gymnasts in June 1994. The necessary experiences, such as test procedures, three-dimensional space calibration, video recording, and digitizing, were obtained from the pilot study. This study was conducted during May and June of 1995. Before the test started, the gymnasts were told about the intention of the project, and their volunteer participation in this study was requested. Those who agreed to participate in the test were also asked to fill out a basic information form, which included their name, age, height, weight, experience, and skill level. The descriptive data of the subjects are shown in Table 1.

Table 1

Descriptive Data of Subjects

Variables	Measures	Begin.	InterM.	Advan.	InterF.
Subjects	n	14	7	6	13
Age	M	10	17	21	13
	SD	2	3	2	2
Height (m)	M	1.38	1.64	1.66	1.58
	SD	0.12	0.10	0.07	0.10
Weight (kg)	M	32.6	58.4	64.6	42.2
	SD	10.5	12.0	8.6	9.2
Experience (years)	M	2	9	15	7
	SD	1	3	1	3
Skill Level		7 to 5	4 to 2	national	7 to 10

Video Recording

Two Panasonics WV-CL 350 color digital cameras were used in this study. The cameras were synchronized for three-dimensional analysis by the Peak Event Synchronization System and operated at the rate of 60 fields per second. The shutter speed was at 1/1000 second. The two cameras were set on tripods at the same level with the center of the calibration frame and on the same side of the vaulting board with the optical axis being approximately 90 degrees. The orientation of the three-dimensional system was with the X-axis aligned along the runway. Y-axis aligned vertically. and Z-axis toward the camera side. as prsented in Figure 1.

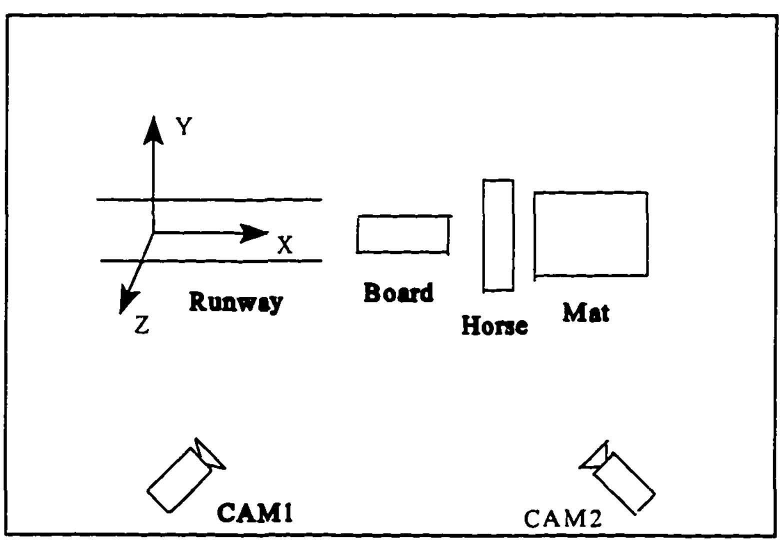


Figure 1. Arrangement of Cameras and Gymnastics Apparatus

The photo field. which covered the last step. hurdle. and board takeoff. was calibrated by using the Peak 25-point Three-Dimensional Calibration Frame for Direct Linear

Transformation. Every subject was filmed twice on the handspring vault. The best trial was selected for three-dimensional analysis.

After video filming, the data were collected by using the Peak5 software system, which included the encoding of videotapes, movement digitizing and editing, parameter calculating, and results display.

Digitizing

Nineteen body points were digitized by the manual data-capture method in every frame from two videotapes. These 19 points were right wrist, right elbow, right shoulder, left shoulder, left elbow, left wrist, right toe, right heel, right ankle, right knee, right hip, left hip, left knee, left ankle, left heel, left toe, right ear, top of head, and right ear. Event frames were identified during the digitizing process to define the six important events: last step takeoff (LST), hurdle foot touchdown (HFT), hurdle foot takeoff (HFO), feet together (FT), board contact (BC), and board takeoff (BT). The events are presented in Figure 2.

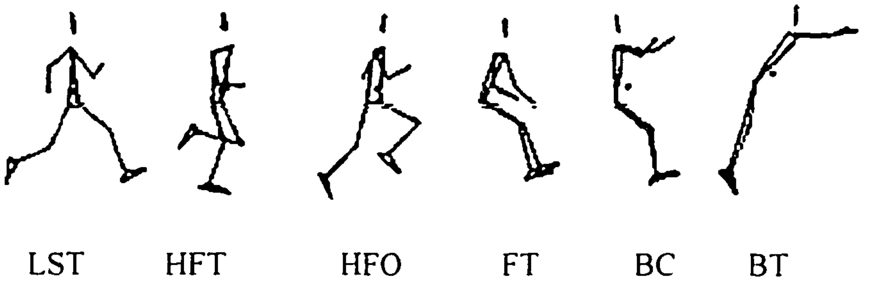


Figure 2. The Six Identified Events

Data Editing

To get the most accuracy on hidden points that could not be seen temporally because of body rotation or were blocked by the body during the process of digitizing, two videotapes were viewed frame by frame before digitizing. During the process of data editing, every path of the digitized points was checked. Some digitized points were redigitized when they were found suspicious. Then, the cubic spline data-conditioning method was used with the filter parameter at optimal filtering option.

Data Calculation

In this study, the Direct Linear Transformation method was used to convert the raw conditioned data from the two cameras into the synchronized three-dimensional coordinate, including the center of mass. Then a three-dimensional parameter calculation program was performed to calculate linear displacement, linear velocity, angular displacement, and angular velocity defined in the Transformation and Angle program.

Display

In this study, all the calculated data for each subject were obtained through combination display on the computer equipped with the Peak5 software system, which could display every single or all the digitized stick figures of every movement and the corresponding linear displacement and linear velocity data at the digitized points, and the center of mass, as well as the defined angular displacement and angular velocity at every frame, including the six defined events. This method ensured that accurate data were gathered.

Data Analysis

The gathered data were analyzed by using the SPSS software programs. The data analysis in this study included (1) the computation of means, standard errors of the means, and standard deviations of all the variables, (2) a correlation analysis, (3) analysis of variance (ANOVA) tests on all the variables among the different skill-level groups, followed by Duncan's Multiple Range Tests. The statistical significance level was set at $p < 0.05$.

Estimate of Accuracy

To maintain the accuracy of image calculation, the standard volume error of the calculation frame was set to be less than 0.5 percent. In this study, the average standard volume error was 0.2 percent or 8.3 millimeters, with a standard deviation of 0.1 millimeter.

CHAPTER 4

Results and Discussion

General Descriptive Data

Previous research has suggested that the horizontal velocity at the center of mass was an important indicator for successful vaulting (Bruggemann, 1987; Takei, 1989). This study calculated means (M), standard errors of the means (SEM), and results of Duncan's Multiple Range Tests for the center of mass horizontal velocities at the last step takeoff, hurdle foot touchdown, hurdle foot takeoff, feet-together position, board contact, and board takeoff among the male beginning skill-level group, male intermediate skill-level group, male advanced skill-level group, and female intermediate skill-level group. The results are displayed in Table 2.

Table 2

The Center of Mass

Horizontal Velocities at Selected Events among the Four Groups

Variables ($m \cdot sec^{-1}$)	A Begin. M SEM	B InterM. M SEM	C Advan. M SEM	D InterF. M SEM
Last step takeoff	$4.88 \pm 0.20^{b,c,d}$	$6.82 \pm 0.17^{a,c,d}$	$7.60 \pm 0.10^{a,b,d}$	$6.26 \pm 0.11^{a,b,c}$
Hurdle foot touchdown	$4.88 \pm 0.20^{b,c,d}$	$6.72 \pm 0.16^{a,c,d}$	$7.47 \pm 0.10^{a,b,d}$	$6.15 \pm 0.12^{a,b,c}$
Hurdle foot takeoff	$4.18 \pm 0.18^{b,c,d}$	$6.56 \pm 0.15^{a,c,d}$	$7.50 \pm 0.11^{a,b,d}$	$5.89 \pm 0.13^{a,b,c}$
Feet together	$4.37 \pm 0.18^{b,c,d}$	$6.44 \pm 0.24^{a,c,d}$	$7.48 \pm 0.12^{a,b,d}$	$5.89 \pm 0.12^{a,b,c}$
Board contact	$4.13 \pm 0.18^{b,c,d}$	$6.24 \pm 0.15^{a,c,d}$	$7.10 \pm 0.13^{a,b,d}$	$5.54 \pm 0.15^{a,b,c}$
Board takeoff	$2.93 \pm 0.12^{b,c,d}$	$4.26 \pm 0.12^{a,c,d}$	$4.70 \pm 0.12^{a,b,d}$	$3.31 \pm 0.31^{a,b,c}$

Note. ^{a,b,c,d} indicate significant differences from group A, B, C, D. $p < 0.05$.

The results in Table 2 confirmed that horizontal velocities at the center of mass were based on the level of performance. The advanced group had significantly faster horizontal velocities during the hurdle and board takeoff than the intermediate and beginning groups. The male intermediate group showed significantly quicker horizontal velocities than the female intermediate group. The beginning group presented slowest horizontal velocities during the hurdle and board takeoff.

In addition to the study of horizontal velocities during the hurdle and board takeoff. appropriate vertical velocities are required for successful vaulting. To reveal the features of vertical velocities among the different skill-level groups during the hurdle and board takeoff. this study calculated the center of mass vertical velocities at the hurdle foot takeoff. feet-together position. board contact. and board takeoff among the four different groups. The results are displayed in Table 3.

Table 3

The Center of Mass

Vertical Velocities at Selected Events among the Four Groups

	A	B	C	D
Variables	Begin.	InterM.	Advan.	InterF.
($m \cdot sec^{-1}$)	M SEM	M SEM	M SEM	M SEM
Hurdle foot takeoff	$1.72 \pm 0.05^{b, c, d}$	1.50 ± 0.07^{a}	1.38 ± 0.08^{a}	1.50 ± 0.08^{a}
Feet together	$-0.88 \pm 0.07^{b, c, d}$	-1.38 ± 0.14^{a}	-1.41 ± 0.04^{a}	-1.31 ± 0.04^{a}
Board contact	-1.33 ± 0.09	-1.25 ± 0.11	-1.04 ± 0.10	-1.07 ± 0.07
Board takeoff	$2.69 \pm 0.13^{b, c, d}$	3.40 ± 0.16^{a}	$4.42 \pm 0.17^{a, d}$	$3.63 \pm 0.08^{a, c}$

Note. [a, b, c, d] indicate significant differences from group A, B, C, D. $p<0.05$.

The results in Table 3 indicated:

1. No significant differences in the center of mass vertical velocities at the event of board contact among the four different groups.

2. At the hurdle foot takeoff, the beginning group had an average vertical velocity of 1.72 meters per second. In comparison, the advanced group demonstrated an average vertical velocity of 1.38 meters per second at the center of mass. Duncan's Multiple Range tests indicated that the center of mass vertical velocity from the beginning group was significantly higher than that of the advanced and intermediate groups. Apparently, the beginning level gymnasts started their hurdle foot takeoff from a higher vertical velocity.

3. At the feet-together position, the advanced group showed an average vertical velocity of -1.41 meters per second at the center of mass, which was significantly greater than -0.88 meter per second from the beginning skill-level group. This indicated that the advanced gymnasts approached the board contact with a greater downward momentum.

4. At board takeoff, both intermediate and advanced groups demonstrated significantly higher vertical velocities than the beginning group. The advanced group showed an average vertical velocity of 4.42 meters per second at board takeoff, which was the highest vertical velocity among the four groups.

Since the analysis and comparison for the center of mass resultant velocity can provide information about actual movement performance, this study calculated the center of mass resultant velocities at the last step takeoff, hurdle foot touchdown, hurdle foot takeoff, feet-together position, board contact, and board takeoff among the four different skill-level groups. The results are displayed in Table 4.

Table 4
The Center of Mass
Resultant Velocities at Selected Events among the Four Groups

Variables ($m \cdot sec^{-1}$)	A Begin. M SEM	B InterM. M SEM	C Advan. M SEM	D InterF. M SEM
Last step takeoff	$4.96 \pm 0.18^{b,c,d}$	$6.83 \pm 0.17^{a,c,d}$	$7.61 \pm 0.11^{a,b,d}$	$6.29 \pm 0.11^{a,b,c}$
Hurdle foot touchdown	$4.95 \pm 0.19^{b,c,d}$	$6.77 \pm 0.16^{a,c,d}$	$7.51 \pm 0.10^{a,b,d}$	$6.17 \pm 0.12^{a,b,c}$
Hurdle foot takeoff	$4.58 \pm 0.16^{b,c,d}$	$6.74 \pm 0.14^{a,c,d}$	$7.64 \pm 0.09^{a,b,d}$	$6.10 \pm 0.12^{a,b,c}$
Feet together	$4.50 \pm 0.17^{b,c,d}$	$6.64 \pm 0.20^{a,c,d}$	$7.62 \pm 0.11^{a,b,d}$	$6.01 \pm 0.13^{a,b,c}$
Board contact	$4.40 \pm 0.16^{b,c,d}$	$6.31 \pm 0.10^{a,c,d}$	$7.20 \pm 0.14^{a,b,d}$	$5.66 \pm 0.15^{a,b,c}$
Board takeoff	$4.07 \pm 0.14^{b,c,d}$	$5.92 \pm 0.08^{a,c,d}$	$6.50 \pm 0.12^{a,b,d}$	$4.93 \pm 0.08^{a,b,c}$

Note. ^{a,b,c,d} indicate significant differences from group A, B, C, D. $p<0.05$.

The results in Table 4 showed that the center of mass resultant velocities also varied with the level of performance during the hurdle and board takeoff. The beginning group had significantly slower resultant velocities than the other groups. The male intermediate group had significantly faster resultant velocities than the female intermediate group at the six selected events. The advanced group indicated significantly faster resultant velocities at the center of mass during the hurdle and board takeoff than the intermediate and beginning groups.

Ratios of Horizontal Velocity Utilization

It has been known that the horizontal velocity varies with the level of performance (Bruggemann, 1987). The findings in this study were in accordance with the previous studies. However, a relative measure of horizontal velocity is also important since the horizontal velocity is associated with age, height, and physical condition. It is very difficult for a young beginning skill-level gymnast to achieve a fast horizontal velocity like an advanced gymnast does. But young gymnasts can be taught to use their horizontal velocity efficiently and make comparisons with advanced gymnasts in a relative measure. A higher ratio of horizontal velocity utilization during the hurdle and board takeoff means less decrease in velocity, and that is what one would expect from the advanced hurdle and board-takeoff techniques. In other words, the lower the ratio, the poorer the hurdle and board-takeoff techniques will be. For this reason, the present study calculated the average ratios for the center of mass horizontal velocity utilization among the four different skill-level groups at the hurdle foot takeoff, feet-together position, board contact, and board takeoff. The results are presented in Table 5.

Table 5

Ratios for the Center of Mass

Horizontal Velocity Utilization at Selected Events among the Four Groups

Variables	A Begin. M SEM	B InterM. M SEM	C Advan. M SEM	D InterF. M SEM
Hurdle foot takeoff	$0.86 \pm 0.02^{b,c,d}$	0.97 ± 0.01^{a}	$1.00 \pm 0.01^{a,d}$	$0.95 \pm 0.01^{a,c}$
Feet together	$0.89 \pm 0.02^{b,c,d}$	$0.95 \pm 0.01^{a,c}$	$1.00 \pm 0.01^{a,b,d}$	$0.96 \pm 0.01^{a,c}$
Board contact	$0.84 \pm 0.02^{b,c,d}$	0.92 ± 0.01^{a}	$0.95 \pm 0.02^{a,d}$	$0.90 \pm 0.01^{a,c}$
Board takeoff	0.59 ± 0.02^{d}	0.63 ± 0.02^{d}	0.63 ± 0.02^{d}	$0.54 \pm 0.01^{a,b,c}$

Note. ^{a,b,c,d} indicate significant differences from group A, B, C, D. $p<0.05$.

The results in Table 5 indicated:

1. The intermediate and advanced groups demonstrated significantly better ratios of horizontal velocity utilization than the beginning group at the hurdle foot takeoff, feet-

together position, and board contact.

2. The male intermediate and advanced groups showed no significant differences from the beginning group on ratios of horizontal velocity utilization at board takeoff.

3. The advanced group, male intermediate group, and beginning group demonstrated significantly higher ratios than the female intermediate group at board takeoff.

General Technique Features of the Hurdle and Board Takeoff

To further understand the general technique features of the hurdle and board takeoff at different skill levels, this study calculated the means, standard errors of the means, and outcomes of Duncan's Multiple Range Tests on the last step length, hurdle length, hurdle flight time, hurdle flight height, hurdle flight angle, and board contact time among the four different groups. The results are presented in Table 6.

Table 6

Last Step Length, Hurdle Length, Hurdle Flight Time, Height, and Angle, and Board Contact Time among the Four Groups

Variables	A Begin. M SEM	B InterM. M SEM	C Advan. M SEM	D InterF. M SEM
Last step length (m)	$1.09 \pm 0.06^{b,c,d}$	1.40 ± 0.09^{a}	1.51 ± 0.02^{a}	1.35 ± 0.04^{a}
Hurdle length (m)	$1.84 \pm 0.07^{b,c,d}$	$2.65 \pm 0.07^{a,d}$	$2.78 \pm 0.08^{a,d}$	$2.40 \pm 0.04^{a,b,c}$
Hurdle flight time (s)	0.29 ± 0.01^{c}	0.26 ± 0.01	0.24 ± 0.01^{a}	0.27 ± 0.01
Hurdle flight height (m)	$0.16 \pm 0.01^{c,d}$	0.13 ± 0.01	0.11 ± 0.01^{a}	0.12 ± 0.01^{a}
Hurdle flight angle (deg)	$26.9 \pm 1.2^{b,c,d}$	$18.3 \pm 1.0^{a,c}$	$11.0 \pm 0.4^{a,b,d}$	$15.6 \pm 1.1^{a,c}$
Board contact time (s)	$0.16 \pm 0.01^{b,c,d}$	0.12 ± 0.00^{a}	$0.10 \pm 0.01^{a,d}$	$0.12 \pm 0.01^{a,c}$

Note. ^{a,b,c,d} indicate significant differences from group A, B, C, D. $p<0.05$.

The results in Table 6 showed:

1. The advanced group had an average of 1.51 meters on the last step length, while the beginning group showed an average of only 1.09 meters. Duncan's multiple comparison tests indicated that both intermediate and advanced groups demonstrated significantly longer strides at the last step than the beginning skill-level group.

2. The advanced group displayed an average of 2.78 meters on the hurdle length, while the beginning group had only 1.84 meters on average. Multiple Range Tests indicated that both intermediate and advanced groups had significantly longer hurdle than the beginning group. In addition, the female intermediate group showed a significantly shorter hurdle distance than the male intermediate and advanced groups.

3. The advanced group covered their long hurdle length in only 0.24 second on average. In comparison, the beginning group spent an average of 0.29 second on the hurdle flight time for a relatively short hurdle distance. Duncan's Multiple Range Tests indicated that the difference of hurdle flight time was significant between the beginning and advanced group.

4. The advanced group demonstrated an average of 0.11 meters for the hurdle flight height and 11.0 degrees for the hurdle flight angle. In contrast, the beginning group showed an average of 0.16 meters on the hurdle flight height and 26.9 degrees on the hurdle flight angle. Multiple comparison tests indicated that the hurdle flight height of the beginning group was significantly higher than that of the advanced group. In addition, the advanced group also demonstrated a significantly lower hurdle flight angle than the beginning and intermediate groups.

5. The advanced group displayed an average board-contact time of 0.10 second, while the beginning group showed an average of 0.16 second. Multiple Range Tests indicated that the difference on board-contact time was significant. The very short board-contact time from the advanced gymnasts indicated a very fast board contact and takeoff technique.

Detailed Technique Features of the Body Segments during the Hurdle and Board Takeoff

In this study, **movement techniques** were defined as the way a gymnast interacts with the outside environment and coordinates the whole body segments, including arms, legs, trunk, and head, in certain space and certain time in order to execute specific movements. The optimal movement techniques were defined as the best possible way that a gymnast interacts with the outside environment and coordinates the whole body segments with the most efficiency and achieves the maximal potential in the execution of movements.

Based on the definition of movement techniques, it is apparently not adequate to conduct a movement analysis which focuses on general technique features only. Instead, a movement-technique analysis should focus on the relative movement of body segments, such as trunk, arms, and legs, as well as their coordination and timing techniques in certain specific time and space. It is also of crucial importance to study the body segment extremities, such as ankles and wrists, because they possess the biggest flexibility and potential in the function of the body-movement chain. Based on this understanding about movement techniques, this study explored the kinematic features of the gymnasts' trunk, arms, and legs, as well as their coordination during the hurdle and board takeoff.

Kinematic Features of Leg-Movement Techniques during the Hurdle and Board Takeoff

In this section, the results are presented in the following way: (1) the angular displacement of the hurdle leg at selected events among the different skill-level groups, (2) the angular displacement, angular velocity, and linear velocity for the knee joint at selected events among the different skill-level groups, (3) the linear velocity of the ankle joint at the selected instants among the four groups, and (4) the timing techniques of the hurdle legs among the different groups. First, this study investigated the angular displacement of the hurdle leg at selected events among the four different skill-level groups. The angular displacement of the leg was defined as the angle between the connection of the ankle-hip joint and the horizontal direction. The means and standard errors of the means for the angular displacement of the leg at the hurdle foot takeoff, feet-together position, board contact, and board takeoff, as well as the results of Duncan's Multiple Range Tests, are presented in Table 7.

Table 7

Angular Displacement

of the Leg at Selected Events among the Four Groups

Variables (deg)	A Begin. M SEM	B InterM. M SEM	C Advan. M SEM	D InterF. M SEM
Hurdle foot takeoff	70.0 ± 1.6[b, c, d]	64.5 ± 2.8[a]	61.9 ± 1.9[a]	63.9 ± 0.9[a]
Feet together	56.1 ± 1.4[d]	53.4 ± 0.8	52.2 ± 1.8	50.5 ± 0.9[a]
Board contact	58.9 ± 1.3[d]	56.6 ± 1.1	55.6 ± 2.1	54.7 ± 1.0[a]
Board takeoff	76.5 ± 1.5[c, d]	75.2 ± 1.9[c, d]	82.4 ± 1.5[a, b]	83.6 ± 1.0[a, b]

Note. [a, b, c, d] indicate significant differences from group A, B, C, D. $p<0.05$.

The results in Table 7 indicated that the beginning group had a significantly larger angular displacement of the leg at the hurdle foot takeoff (70.0 degrees). At the feet-together position and board contact, the beginning group showed significantly larger angular displacements of the leg than the female intermediate group. At board takeoff, the beginning group presented a smaller leg angular displacement (76.5 degrees). In comparison, the advanced group showed smaller angles of the leg at the hurdle foot takeoff (61.9 degrees) and the feet-together position (52.2 degrees). At board takeoff, the advanced group demonstrated a large angular displacement of the leg (82.4 degrees). Apparently, the advanced gymnasts had a better hurdle takeoff position in maintaining the horizontal velocity. They started the blocking action of legs earlier and took off from the board with legs in almost a vertical position.

To further investigate the technique features of the hurdle leg, this study calculated the angular displacement for the hurdle push-off leg knee joint at the hurdle foot takeoff:

the minimum angular displacement during the hurdle: and the angular displacement of the knee joint at the feet-together position. board contact. and board takeoff among the four different skill-level groups. The group means. standard errors of the means. and results of ANOVA tests are presented in Table 8.

Table 8

Angular Displacement

of the Knee Joint at Selected Events among the Four Groups

Variables	A Begin.		B InterM.		C Advan.		D InterF.		
(deg)	M	SEM	M	SEM	M	SEM	M	SEM	F
Hurdle foot takeoff	148	3	146	3	148	2	148	2	0.17
Minimum value	86[d]	6	74	8	69	8	68[a]	3	2.42
Feet together	139	4	142	4	145	4	143	3	0.39
Board contact	144	3	148	2	150	3	147	3	0.72
Board takeoff	171	2	171	2	176	1	170	1	1.35

Note: [a, d] indicate significant differences between group A and D. $p < 0.05$.

The results in Table 8 indicated no significant differences in the angular displacement of the knee joint at the hurdle foot takeoff. feet-together position. board contact. and board takeoff among the four groups. However. Duncan's Multiple Range Tests indicated a significant difference between the average of 86 degrees from the beginning group and the average of 68 degrees from the female intermediate group at the minimum knee joint angular displacement during the hurdle. though the F-value of ANOVA test did not indicated such significant differences among the four groups. The advanced group displayed an average minimum knee joint angular displacement of 69 degrees during the hurdle. which was 17 degrees smaller than that of the beginning group. However. the 17-degree difference did not reach the significant level. It seems that further studies are needed to clarify the technique difference.

To determine if there were differences in the angular velocity at the knee joint among the different groups. this study calculated the maximum angular velocity of the hurdle push-off leg knee joint during the hurdle and the angular velocity at the feet-together position. The results are shown in Table 9.

Table 9

Angular Velocity of the Knee Joint at Maximum Value during the Hurdle and at the Feet-Together Position among the Four Groups

	A		B		C		D		
Variables	Begin.		InterM.		Advan.		InterF.		F
($rad \cdot sec^{-1}$)	M	SEM	M	SEM	M	SEM	M	SEM	
Maximum value	12.0	1.3	14.1	1.3	15.4	1.3	14.8	0.6	1.91
Feet together	7.6	1.4	6.4	1.0	7.2	2.3	6.2	0.8	0.26

Note. one radian = 57.3 degrees.

The results in Table 9 suggested no significant differences in angular velocities of the knee joint during the hurdle among the four different skill-level groups. which indicated that all the different skill-level gymnasts extended their knee joints at the same angular velocity level.

During the hurdle and board-takeoff period. both the free leg and the push-off leg experienced a fast swing forward to the feet-together position. Linear movement apparently is the main feature of the hurdle legs. To determine if there were some differences in the linear movement at the knee joint, this study calculated the maximum linear (resultant) velocity of the hurdle push-off leg knee joint during the hurdle and at the feet-together position and board contact, as well as the linear velocity of the free-leg knee joint at the hurdle foot touchdown and the hurdle foot takeoff. The results are shown in Table 10.

Table 10

Linear Velocities of the Knee Joint at Selected Events among the Four Groups

	A	B	C	D
Variables	Begin.	InterM.	Advan.	InterF.
($m \cdot sec^{-1}$)	M SEM	M SEM	M SEM	M SEM
Push-off leg				
Maximum value	6.48 ± 0.30[b,c,d]	9.19 ± 0.24[a,c]	10.60 ± 0.24[a,b,d]	8.53 ± 0.16[a,c]
Feet together	4.15 ± 0.18[b,c,d]	6.72 ± 0.09[a,c]	7.94 ± 0.17[a,b,d]	6.31 ± 0.13[a,c]
Board contact	4.67 ± 0.17[b,c,d]	6.62 ± 0.18[a,d]	7.24 ± 0.32[a,d]	5.98 ± 0.12[a,b,c]
Free leg				
Hurdle foot touchdown	6.86 ± 0.47[b,c,d]	10.10 ± 0.43[a]	11.10 ± 0.35[a,d]	9.38 ± 0.31[a,c]
Hurdle foot takeoff	5.22 ± 0.27[b,c,d]	8.72 ± 0.26[a,c,d]	10.60 ± 0.29[a,b,d]	7.65 ± 0.38[a,b,c]

Note. [a,b,c,d] indicate significant differences from group A, B, C, D, $p<0.05$.

The results in Table 10 indicated significant differences in linear velocities at the knee joint during the hurdle and takeoff from the board among the four different groups. From the feet-together position to board contact, the intermediate and advanced groups had a tendency of slower linear velocity at the knee joint, while the beginning group had a slight increase in the linear velocity at the knee joint. In addition, the advanced group had a maximum linear velocity of 10.6 meters per second at the knee joint, which was much faster than their center of mass linear velocities during the hurdle and board contact. Apparently, the fast relative movement of body segments was involved during the hurdle.

The results of Duncan's multiple comparison tests also indicated:

1. The beginning group had significantly slower linear velocities at both knee joints during the hurdle and board contact than the intermediate and advanced groups.

2. The advanced group had significantly faster linear velocities on both the hurdle push-off leg and the free leg at the knee joints than the beginning group and female intermediate group.

These results suggested that the less advanced gymnasts tend to swing their free legs slower from the hurdle foot touchdown to the hurdle foot takeoff, and they did not drive their push-off legs forward fast enough when compared with the advanced gymnasts.

To further understand the relative movement techniques of the legs during the hurdle and board takeoff, it is necessary to analyze the relative movement of ankles since they, as the extremity of leg segments, possess the highest potential in the function of the movement chain. This study calculated the horizontal velocities of the push-off leg ankle joint at the maximum value, feet-together position, and board contact; the vertical velocities of the ankle at the feet-together position and board contact; and the resultant velocities of the ankle at the maximum value, feet-together position, and board contact among the four different skill-level groups. The results are presented in Table 11.

Table 11

Horizontal, Vertical and Resultant

Velocities of the Ankle Joint at Selected Events among the Four Groups

Variables (m·sec^{-1})	A Begin. M SEM	B InterM. M SEM	C Advan. M SEM	D InterF. M SEM
Horizontal				
Maximum value	$7.83 \pm 0.39^{b, c, d}$	$12.20 \pm 0.33^{a, c}$	$14.00 \pm 0.41^{a, b, d}$	$11.20 \pm 0.29^{a, c}$
Feet together	$6.07 \pm 0.40^{b, c}$	7.88 ± 0.58^{a}	7.57 ± 0.70^{a}	6.58 ± 0.28
Board contact	$2.22 \pm 0.15^{b, c, d}$	3.89 ± 0.34^{a}	$4.61 \pm 0.40^{a, d}$	$3.45 \pm 0.33^{a, c}$
Vertical				
Feet together	$-0.90 \pm 0.16^{b, c, d}$	$-1.70 \pm 0.36^{a, c}$	$-2.90 \pm 0.35^{a, b, d}$	$-2.10 \pm 0.15^{a, c}$
Board contact	$-1.80 \pm 0.12^{b, c, d}$	-2.80 ± 0.12^{a}	$-3.10 \pm 0.21^{a, d}$	$-2.50 \pm 0.15^{a, c}$
Resultant				
Maximum value	$8.01 \pm 0.39^{b, c, d}$	$12.40 \pm 0.34^{a, c}$	$14.20 \pm 0.36^{a, b, d}$	$11.40 \pm 0.29^{a, c}$
Feet together	$6.27 \pm 0.42^{b, c}$	8.19 ± 0.56^{a}	8.17 ± 0.70^{a}	7.00 ± 0.26
Board contact	$2.95 \pm 0.14^{b, c, d}$	$4.53 \pm 0.19^{a, c}$	$5.71 \pm 0.43^{a, b, d}$	$4.33 \pm 0.30^{a, c}$

Note. $^{a, b, c, d}$ indicate significant differences from group A, B, C, D. $p < 0.05$.

The results in Table 11 showed that the beginning group had significantly slower horizontal, vertical, and resultant velocities at the ankle joint than the advanced group during the hurdle and board contact period. In comparison, the advanced group demonstrated significantly faster relative movements at the ankle joint. The maximum horizontal and resultant velocity during the hurdle was 14.0 and 14.2 meters per second, respectively, which was also significantly faster than horizontal velocities at the center of mass during the hurdle.

During the hurdle and board takeoff, the legs not only went through a fast relative movement, but also involved timing techniques, such as the time from the feet-together position to board contact and the knee flexion before the forceful extension during the very short period of board contact. To determine if there were significant differences in the timing techniques of the legs, this study calculated the average time difference from the feet-together position to board contact and the knee flexion during board contact. The means, standard errors of the means, and results of Duncan's Multiple Range Tests are shown in Table 12.

Table 12

The Timing Features of Legs at Selected Instants among the Four Groups

Variables	A Begin. M SEM	B InterM. M SEM	C Advan. M SEM	D InterF. M SEM
Time difference (sec)	$0.07 \pm 0.01^{b,c,d}$	0.03 ± 0.01^{a}	0.02 ± 0.00^{a}	0.03 ± 0.00^{a}
Knee flexion (deg)	$20.2 \pm 2.1^{b,c,d}$	$13.0 \pm 2.5^{a,c}$	$2.6 \pm 0.9^{a,b}$	7.5 ± 2.0^{a}

Note. ^{a,b,c,d} indicate significant differences from group A, B, C, D, $p<0.05$.

The results in Table 12 indicated that the beginning group had a significantly longer time from the feet-together position to board contact than the other skill-level groups, and this group also had a significantly larger knee flexion during board contact than the advanced and female intermediate groups. In comparison, the advanced group had the shortest time (0.02 second) from the feet-together position to board contact and the smallest knee flexion (2.6 degrees) during the board contact period. These findings suggested that the advanced gymnasts used very active board contact and takeoff techniques. They started the feet-together position just moment before board contact, and they experienced a quick and powerful extension at the knee joints.

Kinematic Features of Trunk-Movement

Techniques during the Hurdle and Board Takeoff

During the hurdle and board takeoff, trunk-movement techniques play an important role for a smooth transition and a proper board takeoff. The position of the trunk segment, which represents about 50 percent of total mass, can affect the location of the center of mass in a significant way. Therefore, this study investigated the angular displacement of the hip joint and the angular displacement of the trunk at selected events during the hurdle and board takeoff. First, this study calculated the angular displacement of the hip joint, which was defined by the connection of the shoulder-hip-knee joint, on the side of the hurdle push-off leg, as well as the side of the free leg at the hurdle foot takeoff, and the average angular displacement of both hip joints at the feet-together position, board contact, and board takeoff. The results are displayed in Table 13.

Table 13
Angular Displacement
of the Hip Joint at Selected Events among the Four Groups

Variables (deg)	A Begin. M SEM	B InterM. M SEM	C Advan. M SEM	D InterF. M SEM	F
Hurdle foot takeoff (push off leg)	181 ± 4[c]	187 ± 3	193 ± 2[a]	189 ± 2	2.54
Hurdle foot takeoff (free leg)	114 ± 3	119 ± 3	121 ± 2	120 ± 2	1.56
Feet together	106 ± 4	99 ± 2	99 ± 4	98 ± 2	1.60
Board contact	114 ± 3	109 ± 2	110 ± 3	109 ± 2	1.19
Board takeoff	150 ± 3	153 ± 2	145 ± 3	147 ± 2	1.24

Note: [a, c] indicate significant differences between group A and C. $p < 0.05$.

The results in Table 13 indicated that there were no significant differences in the hip angular displacement at the hurdle foot takeoff (free leg side), feet-together position, board contact, and board takeoff among the four different skill-level groups. However, Duncan's Multiple Range Tests indicated a significant difference in the hip joint angular displacement at the hurdle foot takeoff (push-off leg side) between the beginning and advanced group. This difference suggested that the advanced gymnasts started the hurdle step with fully extended hip joint. In comparison, the beginning skill-level gymnasts did not fully extend the hip joint at the hurdle foot takeoff.

Since the angular displacement of the hip joint was connected by the same-side shoulder and knee joints, this variable cannot fully represent the relative movement of the trunk. For this reason, this study also calculated the angular displacement of the trunk by comparing the trunk position with the vertical line. The results of the angular displacement of the trunk at the hurdle foot takeoff, feet-together position, board contact, and board takeoff are presented in Table 14.

Table 14

Angular Displacement of the Trunk at Selected Events among the Four Groups

	A	B	C	D	
Variables	Begin.	InterM.	Advan.	InterF.	
(deg)	M SEM	M SEM	M SEM	M SEM	F
Hurdle foot takeoff	3.9 ± 1.8	3.0 ± 1.0	2.6 ± 0.8	2.2 ± 1.3	0.28
Feet together	20.8 ± 2.3	25.8 ± 1.4	23.7 ± 1.1	26.0 ± 1.3	1.89
Board contact	17.8 ± 2.5	22.1 ± 2.0	20.4 ± 1.5	20.7 ± 1.3	0.74
Board takeoff	40.8 ± 2.2	43.1 ± 2.9	40.0 ± 1.1	40.7 ± 2.1	0.22

The results in Table 14 indicated no significant differences in the angular displacement of the trunk during the hurdle and board takeoff among the four different skill-level groups. The trunk angular displacements ranged from 2.2 to 3.9 degrees at the hurdle foot takeoff, 20.8 to 26 degrees at the feet-together position, 17.8 to 22.1 degrees at board contact, and 40 to 43.1 degrees at board takeoff among the four groups.

It was interesting to note that the trunk forward inclination showed slight decreases among the four groups from the feet-together position to board contact. This fact indicated a slight backward rotation of the trunk during the very short period. However, this finding did not indicate a backward lean of the trunk. The average trunk forward inclination was still about 20 degrees among the different skill-level gymnasts.

Kinematic Features of Arm-Movement Techniques during the Hurdle and Board Takeoff

Compared with the whole body weight, the arms represent about 10 percent of the total body weight (Hay, 1993). However, as part of the body-movement chain, the fast relative arm movement can have a significant impact on the whole body movement. To investigate if there were significant differences in arm-movement techniques among the different skill-level groups, this study explored the angular displacement and angular velocity at the shoulder joint and the linear velocity at the wrist joint, as well as the arm-movement styles. First, this study examined the angular displacement of the shoulder joint at the feet-together position, board contact, and board takeoff. The results are displayed in Table 15.

Table 15

Angular Displacement

of Shoulder Joint at Selected Events among the Four Groups

Variables (deg)	A Begin. M ± SEM	B InterM. M ± SEM	C Advan. M ± SEM	D InterF. M ± SEM	F
Feet together	10 ± 13[c, d]	47 ± 20[c, d]	98 ± 7[a, b]	89 ± 6[a, b]	13.28**
Board contact	41 ± 9[b, c, d]	71 ± 13[a, c, d]	107 ± 7[a, b]	101 ± 5[a, b]	13.97**
Board takeoff	110 ± 4[b, c, d]	131 ± 4[a]	134 ± 3[a]	128 ± 3[a]	9.23**

Note. [a, b, c, d] indicate significant differences from group A, B, C, D. $p<0.05$.

The results in Table 15 indicated:

1. The beginning group had significantly smaller angular displacements at the shoulder joint than the advanced group and female intermediate group at the feet-together position, board contact, and board takeoff.

2. The advanced group had significantly larger angular displacements at the shoulder joint than the male intermediate group at the feet-together position and board contact. At board takeoff, no significant differences were found in the angular position at the shoulder joint between the advanced and intermediate group.

3. The angular displacements at the shoulder joint ranged from 128 degrees to 134 degrees among the intermediate and advanced gymnasts at the board takeoff. In comparison, the beginning skill-level gymnasts showed an average angular displacement of 110 degrees at the shoulder joint. Apparently, the beginning level gymnasts did not fully extend their shoulder joints at the board takeoff.

The fast swing of the arms during the hurdle and board takeoff means that the fast angular velocity at the shoulder joint was also actively involved. To determine the angular velocity at the shoulder joint during the hurdle and board takeoff among the four different groups, this study calculated the shoulder joint angular velocity at the maximum value during the hurdle, feet-together position, board contact, and board takeoff. The results are presented in Table 16.

Table 16

Shoulder Joint Angular Velocity at Selected Events among the Four Groups

Variables ($deg \cdot sec^{-1}$)	A Begin. M ± SEM	B InterM. M ± SEM	C Advan. M ± SEM	D InterF. M ± SEM	F
Maximum value	642 ± 32	782 ± 43^{d}	661 ± 79	559 ± 38^{b}	3.78*
Feet Together	-79 ± $110^{b, c, d}$	375 ± 169^{a}	480 ± 64^{a}	365 ± 54^{a}	6.64**
Board Contact	356 ± 72^{b}	665 ± $70^{a, d}$	482 ± 69	433 ± 52^{b}	2.89*
Board Takeoff	294 ± 64^{b}	83 ± 86^{a}	202 ± 81	96 ± 54	2.40

Note. $^{a, b, c, d}$ indicate significant differences from group A, B, C, D. $p<0.05$.

The results in Table 16 indicated:

1. The male intermediate group showed a significantly faster shoulder joint angular velocity than the female intermediate group at the maximum value during the hurdle and board takeoff.

2. The beginning gymnasts swung their arms significantly slower than the male intermediate gymnasts at the feet-together position and board contact. However, at board takeoff the beginning group showed a significantly greater shoulder joint angular velocity than the male intermediate group. Apparently, the beginning skill-level gymnasts swung

their arms in a different way. From board contact to board takeoff. the intermediate and advanced gymnasts showed quick decreases in shoulder joint angular velocity. This technique feature of arm movement was not shown by the beginning skill-level gymnasts.

It is a fact that not only the angular motion of the arms is involved during the hurdle and board takeoff. but the linear movement of the arms is also actively involved. Since the wrist is an ending joint and has the greatest flexibility and potential in the biomechanical movement chain of the arms. this study searched the linear velocity at the wrists during the hurdle and board takeoff. First. this study calculated resultant velocities of the wrists at the maximum value during the hurdle and board takeoff. at the feet-together position. board contact. and board takeoff among the four groups. The results are presented in Table 17.

Table 17

Resultant Velocities of the Wrists at Selected Events among the Four Groups

	A	B	C	D	
Variables	Begin.	InterM.	Advan.	InterF.	
($m \cdot sec^{-1}$)	M ± SEM	M ± SEM	M ± SEM	M ± SEM	F
Maximum value	$8.20 \pm 0.33^{b, c}$	$11.7 \pm 0.64^{a, d}$	$12.50 \pm 0.65^{a, d}$	$8.96 \pm 0.46^{b, c}$	16.68**
Feet together	$6.69 \pm 0.52^{b, c}$	$10.2 \pm 0.69^{a, d}$	$9.54 \pm 0.71^{a, d}$	$7.33 \pm 0.49^{b, c}$	7.46**
Board contact	7.32 ± 0.50^{b}	$10.4 \pm 0.89^{a, d}$	8.84 ± 0.61^{d}	$6.84 \pm 0.46^{b, c}$	6.56**
Board takeoff	$4.99 \pm 0.35^{b, c, d}$	$7.0 \pm 0.18^{a, c}$	$8.68 \pm 0.14^{a, b, d}$	$6.49 \pm 0.33^{a, c}$	17.43**

Note. [a, b, c, d] indicate significant differences from group A, B, C, D. $p<0.05$.

The results in Table 17 indicated:

1. The beginning group showed a maximum resultant velocity of 8.20 meters per second on average at the wrists, which was significantly slower than the 11.7 meters per second and 12.5 meters per second from the advanced and male intermediate groups, respectively, at the maximum value.

2. The male intermediate group demonstrated significantly faster resultant velocities at the wrists than the female intermediate group at the maximum value, feet-together position, and board contact.

3. The advanced group showed no significant differences in resultant velocities of the wrists from the male intermediate group at the maximum value, feet-together position, and board contact. However, at board takeoff, the advanced group presented an average resultant velocity of 8.68 meters per second at the wrists, which was significantly faster than that from the beginning and intermediate groups. This finding indicated that the advanced gymnasts swung their arms differently at board takeoff.

The comparison and analysis of resultant velocities at the wrists among the four groups presented general technique information about the technique difference of arm movement. To further investigate detailed technique differences of arm movement, this study also calculated the horizontal and vertical velocities of the wrists at the maximum value, feet-together position, board contact, and board takeoff. The results are displayed in Table 18.

Table 18

Horizontal and Vertical Velocities

of the Wrists at Selected Events among the Four Groups

Variables	A Begin.	B InterM.	C Advan.	D InterF.
($m \cdot sec^{-1}$)	M SEM	M SEM	M SEM	M SEM
Horizontal				
Maximum value	$7.66 \pm 0.37^{b, c}$	$11.00 \pm 0.78^{a, d}$	$11.90 \pm 0.66^{a, d}$	$8.64 \pm 0.43^{b, c}$
Feet together	$5.83 \pm 0.62^{b, c}$	$9.25 \pm 0.74^{a, d}$	8.23 ± 0.55^{a}	6.42 ± 0.46^{b}
Board contact	6.57 ± 0.50^{b}	$9.08 \pm 1.01^{a, d}$	7.48 ± 0.41^{d}	$5.52 \pm 0.38^{b, c}$
Board takeoff	$3.96 \pm 0.47^{b, c, d}$	$6.59 \pm 0.14^{a, c}$	$8.60 \pm 0.19^{a, b, d}$	$6.18 \pm 0.32^{a, c}$
Vertical				
Maximum value	3.67 ± 0.31^{b}	$5.70 \pm 0.46^{a, d}$	4.91 ± 0.58	3.76 ± 0.33^{b}
Feet together	$-1.00 \pm 0.53^{b, c, d}$	$2.03 \pm 1.11^{a, c}$	$4.45 \pm 0.59^{a, b, d}$	$2.56 \pm 0.31^{a, c}$
Board contact	$1.24 \pm 0.55^{b, c, d}$	4.40 ± 0.52^{a}	$5.33 \pm 1.05^{a, d}$	$3.36 \pm 0.35^{a, c}$
Board takeoff	1.14 ± 0.47	0.97 ± 0.54	0.15 ± 0.35	0.19 ± 0.24

Note. $^{a, b, c, d}$ indicate significant differences from group A. B. C. D. $p < 0.05$.

The results in Table 18 indicated:

1. At board takeoff. the wrist vertical velocities ranged from 0.15 meter per second to 1.14 meters per second. No significant differences were detected among the four groups. Obviously. all the groups showed stop or slow down of the upward swing at the wrists.

2. Horizontally. the beginning skill-level gymnasts swung their wrists significantly slower than the advanced gymnasts did at the maximum horizontal velocity. feet-together position. and board takeoff. Vertically. the beginning level gymnasts also swung their

wrists significantly slower than the advanced gymnasts did at the feet-together position and board contact.

3. From the board contact to board takeoff, the advanced gymnasts showed no signs of slowing down in the wrist horizontal velocity. In comparison, the beginning gymnasts presented an obvious slowing down at the wrist.

4. At board takeoff, the advanced gymnasts demonstrated an average wrist horizontal velocity of 8.60 meters per second. It was not only significantly faster than the average of 3.96 meters per second from the beginning group, but significantly quicker than that from the intermediate groups. Apparently, the advanced gymnasts showed one of their technique differences of arm swing by quickly reaching the hands forward at board takeoff.

5. From the feet-together position to board contact, a large upward vertical velocity from the wrists was needed to gain increased impact on the spring board. The advanced gymnasts showed significantly greater vertical velocities at the wrists than the beginning and female intermediate gymnasts did.

<u>Arm-Movement Patterns during the</u>

<u>Hurdle and Board Takeoff</u>

The differences in shoulder angular displacements and shoulder angular velocities, as well as the differences in linear velocities at the wrists among the four different groups indicated different arm-movement styles and techniques. To examine how the arms were involved during the hurdle and board takeoff, this study analyzed different arm-movement styles among the subjects. The frame-by-frame motion analysis revealed six different arm-movement techniques among the four groups of gymnasts.

The first type of arm-movement style maintains a normal sprinting position with one arm in front of the body and the other arm behind the body at the hurdle foot takeoff. During the hurdle, the hands swing to both sides of the body: then both hands swing vigorously forward and upward. This type of arm-movement style during the hurdle and board takeoff is named the "natural sprinting style." A sample of the digitized arm-movement sequence of this style is presented in Figure 3.

Figure 3. Natural Sprinting Style

The second type of arm-movement style is featured by swinging both hands backward at the hurdle foot takeoff. Then both arms swing straight forward from the back through the hands on both sides, which is followed by a fast forward-and-upward swing. This type of arm-movement style is named the "straight swing style." A sample of the stick figure sequences is shown in Figure 4.

Figure 4. Straight Swing Style

The third type of arm-movement style is characterized by placing both hands in an upward or beside-the-shoulder position at the hurdle foot takeoff. Then both arms swing sideways down to the position where the hands are in front of the body, followed by a forward-and-upward arm swing. This kind of arm-swing style is named the "big sideways circling style." A typical arm-movement sequence is displayed in Figure 5.

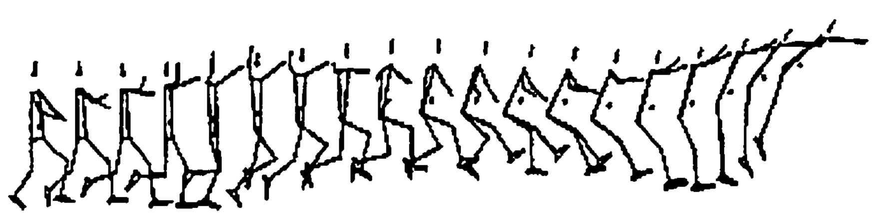


Figure 5. Big Sideways Circling Style

The fourth type of arm-movement style is featured by flexed arms with both hands in front of the body at the hurdle foot takeoff. Then both hands draw a relatively small sideways circle before swinging both hands forward. This type of arm swing is named the "small sideways circling style." A sample movement style is shown in Figure 6.

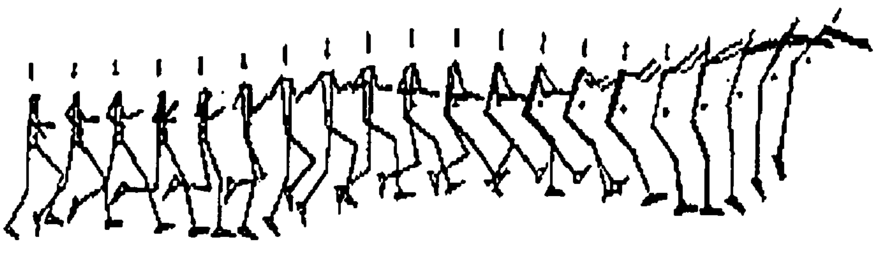


Figure 6. Small Sideways Circling Style

The fifth type of arm-movement style is featured by both arms in an upward position at the hurdle foot takeoff, followed by a downward swing of both arms before the upward- and-forward swing. It is named the "hands up-and-down style." A sample movement sequence is displayed in Figure 7.

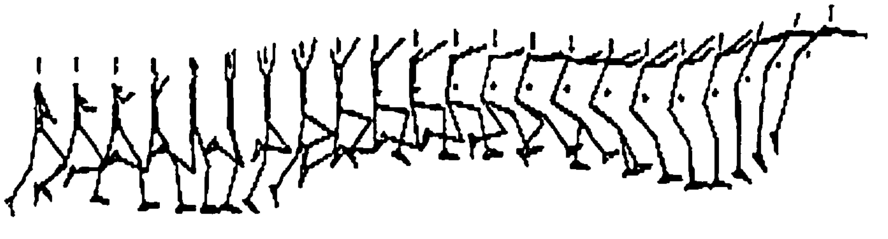


Figure 7. Hands Up-and-Down Style

The last type of arm-movement style found in this study is featured by flexed arms with hands in front of the body at the hurdle foot takeoff, followed by both hands reaching forward with little upward swing. This type of arm movement is named the "hands reaching forward style." An example is shown in Figure 8.

Figure 8. Hands Reaching-Forward Style

To further investigate the arm-movement styles used by the different groups. this study examined every arm-movement style among the four different skill-level groups. The results are shown in Table 19.

Table 19

Arm Movement Styles Used by the Four Groups

Styles	Begin.		InterM.		Advan.		InterF.	
	n	%	n	%	n	%	n	%
Natural sprinting	2	14	3	50	-	-	-	-
Straight swing	1	8	-	-	-	-	-	-
Big sideways Circling	7	50	3	50	3	50	5	39
Small sideways Circling	1	8	-	-	3	50	3	23
Hands Up & Down	-	-	-	-	-	-	2	15
Hands Reaching Forward	3	21	-	-	-	-	3	31

The classification of arm-movement styles among the four groups indicated:

1. The beginning group had the most variety of arm-movement styles.

2. The male intermediate group had arm-movement styles in the natural sprinting and big sideways circling categories.

3. The advanced group featured their arm-swing styles in the big and small sideways circling categories.

4. The female intermediate group displayed four different types of arm-movement techniques, excluding the natural sprinting and straight swing styles.

If all the gymnasts were treated as one group, the largest sample group which included 18 subjects (46 percent) used the big sideways circling swing style. The second popular arm-movement style was the small sideways circling swing technique. Seven (18 percent) of the total subjects adopted this style. The third popular style was the hands reaching forward with little arm swing (15 percent). The order for the remaining styles was natural sprinting (13 percent), hands up and down (5 percent), and straight swing (3 percent).

Body Segmental Coordination Techniques during the Period of the Feet-Together Position, Board Contact, and Board Takeoff

According to the previously defined concept of movement techniques, the analysis of movement techniques should not only study the general and detailed features of the body movements, but also search for segment-coordination techniques. During the period of the feet-together position, board contact, and board takeoff, the body segments, such as legs, trunk, and arms, are required to coordinate closely to produce a powerful board takeoff (Hay, 1993). To study how the gymnasts coordinate their body segments, this study explored angular velocity changes at the knee, hip, and shoulder joints, as well as linear velocity changes from the wrist, shoulder, hip, and knee joints. A change in this study was defined as an obvious increase or decrease of angular or linear velocity. The mixed changes were defined as the appearance of increases and decreases in angular or linear velocity. First, this study examined the changes of angular velocities of knee, hip, and shoulder joints from the feet-together position to board contact among the four different groups. The results are shown in Table 20.

Table 20

Segmental Coordination of Angular Velocities

from the Feet-Together Position to Board Contact among the Four Groups

Variables	Velocity	Begin.		InterM.		Advan.		InterF.	
(deg·sec^{-1})	Pattern	n	%	n	%	n	%	n	%
Angular velocity	Increase	-	-	-	-	1	17	1	8
at knee joint	Decrease	14	100	6	100	5	83	12	92
	Mixed	-	-	-	-	-	-	-	-
Angular velocity	Increase	10	71	6	100	6	100	12	92
at hip joint	Decrease	2	14	-	-	-	-	-	-
	Mixed	2	14	-	-	-	-	1	8
Angular velocity	Increase	12	86	6	100	6	100	11	85
at shoulder joint	Decrease	-	-	-	-	-	-	1	8
	Mixed	2	14	-	-	-	-	1	8

The results in Table 20 indicated:

1. During the period of the feet-together position to board contact, the angular velocity at the knee joint generally had the tendency to decrease.

2. The angular velocities of the hip joint were on an increase in most cases, except four beginning gymnasts and one female intermediate gymnast who had decreased or mixed angular velocities at the hip joint.

3. The angular velocities of the shoulder joint were mostly increases, except two advanced gymnasts and one female intermediate gymnast who had mixed angular velocities at the shoulder joint.

To investigate how the angular velocities at segment joints were coordinated during the period of board contact, the best way is to analyze all the angular velocity patterns involved. However, since every gymnast had a unique pattern of angular velocity coordination, this study only analyzed some common coordination features among the different groups. Two changes in angular velocity were defined by an increase followed by a decrease, or a decrease followed by an increase. Three changes in angular velocity were defined by an increase, followed by a decrease and an increase, or a decrease, followed by an increase and a decrease. The changes of angular velocity at the knee, hip, and shoulder joints among the four different groups during the period of board contact were organized in Table 21.

Table 21

Segmental Coordination

of Angular Velocity during Board Contact among the Four Groups

Variables	Velocity	Begin.		InterM.		Advan.		InterF.	
(deg·sec^{-1})	pattern	n	%	n	%	n	%	n	%
Knee joint	4-Change	-	-	-	-	-	-	1	8
	3-Change	10	71	6	100	3	50	10	77
	2-Change	4	29	-	-	2	33	1	8
	1-Change	-	-	-	-	1	17	1	8
	M & SD	3	1	3	0	2	1	3	1
Hip joint	3-Change	8	57	1	17	-	-	1	8
	2-Change	6	43	2	33	2	33	10	77
	1-Change	-	-	3	50	4	67	2	15
	M & SD	3	1	2	1	1	1	2	1
Shoulder joint	4-Change	1	7	-	-	-	-	-	-
	3-Change	7	50	1	17	1	17	5	39
	2-Change	4	29	4	67	4	67	7	54
	1-Change	2	14	1	17	1	17	1	8
	M & SD	3	1	2	1	2	1	2	1

The results in Table 21 indicated that the advanced group generally had fewer changes in the angular velocity at the knee, hip, and shoulder joints than the beginning group during the period of board contact. These results also suggested that the advanced gymnasts had a relatively better and smoother coordination during board contact than the beginning skill-level gymnasts.

To examine the segmental coordination of angular velocity at board takeoff, this study recorded the tendency of the angular velocity of the knee, hip, and shoulder joints at board takeoff among the four groups. The results are presented in Table 22.

Table 22

Segmental Coordination

of Angular Velocity at the Board Takeoff among the Four Groups

Variables ($deg \cdot sec^{-1}$)	Velocity Pattern	Begin. n	Begin. %	InterM. n	InterM. %	Advan. n	Advan. %	InterF. n	InterF. %
Knee joint	Increase	2	14	-	-	-	-	1	8
	Steady	-	-	-	-	1	17	3	23
	Decrease	12	86	6	100	5	83	9	69
Hip joint	Increase	3	21	1	17	4	67	1	8
	Steady	1	7	-	-	2	33	-	-
	Decrease	10	71	5	83	-	-	12	92
Shoulder joint	Increase	7	50	1	17	2	33	8	62
	Steady	-	-	5	83	2	33	-	-
	Decrease	7	50	-	-	2	33	5	39

The results in Table 22 indicated that the angular velocity at the knee joint tended to decrease at board takeoff in most cases, while a few gymnasts from the beginning group and female intermediate group showed increases. Most advanced gymnasts showed an increase in the angular velocity at the hip joint, while most other gymnasts showed a decrease in the angular velocity of the hip joint at board takeoff. The pattern in the angular velocity of the shoulder joint at board takeoff was not clear among the four groups. For example, some of the advanced gymnasts demonstrated increases, some steady, and some decreases in angular velocity at the shoulder joint. Therefore, how the angular velocity at the shoulder was coordinated with other segments was not clear from this study.

Since the segmental coordination of angular velocity during the hurdle and board takeoff is only one aspect of coordination techniques, this study also explored the segment coordination of linear (resultant) velocity. First, this study searched the linear velocity at the wrist, shoulder, hip, and knee joints from the feet-together position to board contact. The results are presented in Table 23.

Table 23

Segmental Coordination of Linear Velocity

from the Feet-Together Position to Board Contact among the Four Groups

Variables	Velocity	Begin.		InterM.		Advan.		InterF.	
$(m \cdot sec^{-1})$	Pattern	n	%	n	%	n	%	n	%
Wrist joint	Increase	11	79	2	33	2	33	1	8
	Steady	-	-	-	-	-	-	1	8
	Decrease	3	21	4	67	4	67	11	85
Shoulder joint	Increase	3	21	-	-	-	-	-	-
	Steady	3	21	2	33	2	33	-	-
	Decrease	8	57	4	67	4	67	13	100
Hip joint	Increase	11	79	6	100	6	100	12	92
	Steady	1	7	-	-	-	-	1	8
	Decrease	2	14	-	-	-	-	-	-
Knee joint	Increase	13	93	5	83	4	67	11	85
	Steady	1	7	1	17	2	33	2	15
	Decrease	-	-	-	-	-	-	-	-

The results in Table 23 indicated:

1. During the period of the feet-together position to board contact, most of the beginning group showed an increase in linear velocity at the wrist, while most of the intermediate and advanced groups showed a decrease.

2. In most cases, the linear velocity at the shoulder joint showed decreases during this very short period. However, there were about 21 percent of the beginning group who showed increases.

3. The linear velocity at the hip joint showed increases in the majority of cases during this period of time, while three gymnasts from the beginning group and the female intermediate group showed decreases.

4. The linear velocity at the knee joint among all the different groups was steady or showed an increase from the feet-together position to board contact.

To further examine the segmental coordination of linear velocity during the period of board contact, this study checked the changes of linear velocity at the wrist, shoulder, hip, and knee joints, as well as their synchronized coordination number (Sync.). The counting for the synchronized coordination was based on the number of momentary synchronized increases of linear velocities at the wrist, shoulder, hip, and knee joints during the period of board contact. Two synchronization means two of the wrist, shoulder, hip, and knee joints were momentarily synchronized. The results are presented in Table 24.

Table 24

Segmental Coordination of Linear Velocity

from the Board Contact to Board Takeoff among the Four Groups

Variables	Velocity	Begin.		InterM.		Advan.		InterF.	
(m·sec⁻¹)		n	%	n	%	n	%	n	%
Wrist joint	3-Change	2	14	-	-	-	-	5	39
	2-Change	7	50	1	17	4	67	4	31
	1-Change	5	36	5	83	2	33	4	31
	M & SD	2	1	1	1	2	1	2	1
Shoulder joint	3-Change	1	7	1	17	-	-	7	54
	2-Change	9	64	3	50	4	67	6	46
	1-Change	4	29	2	33	2	33	-	-
	M & SD	2	1	2	1	2	1	3	1
Hip joint	3-Change	3	21	1	17	-	-	6	46
	2-Change	11	79	5	83	5	83	7	54
	1-Change	-	-	-	-	1	17	-	-
	M & SD	2	1	2	1	2	1	3	1
Knee joint	3-Change	3	21	-	-	-	-	1	8
	2-Change	11	79	6	100	6	100	12	92
	M & SD	2	1	2	0	2	0	2	0
Number of Sync.	4 Syn.	3	21	2	33	5	83	7	54
	3 Syn.	11	79	4	67	1	17	5	39
	2 Syn.	-	-	-	-	-	-	1	8
	M & SD	3	1	3	1	4	1	4	1

The results in Table 24 revealed:

1. All of the advanced gymnasts experienced two or less changes in the linear velocity at the wrists from the board contact to takeoff. In comparison. 14 percent from the beginning group and 39 percent from the intermediate group experienced three

changes during this short period.

2. 83 percent of the advanced gymnasts experienced two or one changes in the linear velocity at the shoulder joint during the board contact. In contrast, 54 percent of the female intermediate gymnasts showed three changes.

3. None of the advanced group had more than two changes in linear velocity at the hip joint. In comparison, 21 percent of the beginning group and 46 percent of the female intermediate group experienced three changes in the linear velocity at the hip joint during the board contact period.

4. All of the advanced and male intermediate groups experienced two changes in the linear velocity at the knee joint during the period of board contact. While not all of the beginning and female intermediate groups had the same two changes, 21 percent of the beginning gymnasts showed three changes in the linear velocity at the knee joint.

5. The synchronization analysis on the linear velocities at the wrist, shoulder, hip, and knee joints indicated that the advanced group had a higher percentage (83 percent) of the four segmental synchronization during the board contact period. In comparison, only 21 percent of the beginning group, 33 percent of the male intermediate group, and 53 percent of the female intermediate group demonstrated the four segmental synchronization.

To further examine the coordination techniques of segmental linear velocity at board takeoff, this study searched linear velocity patterns of the wrist, shoulder, hip, and knee joints at board takeoff. The results are shown in Table 25.

Table 25

Segmental Coordination

of Linear Velocity at the Board Takeoff among the Four Groups

Variables (m·sec⁻¹)	Velocity Pattern	Begin. n	Begin. %	InterM. n	InterM. %	Advan. n	Advan. %	InterF. n	InterF. %
Wrist joint	Increase	3	21	-	-	4	67	2	15
	Steady	-	-	-	-	1	17	-	-
	Decrease	11	79	6	100	1	17	11	85
Shoulder joint	Increase	7	50	2	33	4	67	3	23
	Steady	-	-	-	-	-	-	-	-
	Decrease	7	50	4	67	2	33	10	77
Hip joint	Increase	10	71	5	83	5	83	8	62
	Steady	-	-	1	17	1	17	-	-
	Decrease	4	29	-	-	-	-	5	39
Knee joint	Increase	10	71	6	100	6	100	11	85
	Steady	-	-	-	-	-	-	1	8
	Decrease	4	29	-	-	-	-	1	8

The results in Table 25 indicated:

1. The linear velocity at the wrist was either steady or increasing among 83 percent of the advanced group during board takeoff. In contrast, 79 percent of the beginning group, 100 percent of the male intermediate group, and 85 percent of the female intermediate group experienced a decrease in the linear velocity of the wrist.

2. Four advanced gymnasts (67 percent) demonstrated an increase of linear velocity at the shoulder joint. In comparison, there were only 50 percent in the beginning group, 33 percent in the male intermediate group, and 23 percent in the female intermediate group that showed increases of linear velocity at the shoulder joint.

3. At board takeoff. none of the advanced group had a decreased linear velocity at the hip joint. However. not all of the beginning and intermediate groups demonstrated the same pattern. There were 29 percent of the beginning group and 39 percent of the female intermediate group who displayed decreased linear velocities at the hip joint.

4. All of the advanced and male intermediate groups showed increases in linear velocity at the knee joint. In comparison. four beginning gymnasts (29 percent) and one female intermediate gymnast (8 percent) showed decreased linear velocity at the knee joint. In general. Table 25 indicated that at the instant of board takeoff the majority of the advanced gymnasts showed increases in the linear velocity at the wrist. shoulder. hip. and knee joints. while few gymnasts in the other groups had the same pattern of coordination.

Body Angular Velocity

at Board Takeoff

A previous study has indicated that a large angular momentum at board takeoff was an important factor for successful vaulting (Takei. 1989). According to the equation of angular momentum

$$H = IW \text{ (I-moment of inertia. W-angular velocity)}$$

if the moment of inertia is set at a certain level. the increase of angular velocity will result in the increase of angular momentum. To investigate whether there was a significant difference in body angular velocity among the different skill-level groups. this study calculated the mean and standard deviation of body angular velocity at board takeoff. The results are displayed in Table 26.

Table 26

Body Angular Velocity at Board Takeoff among the Four Groups

Variable (deg·sec^{-1})	A Begin. M ± SEM	B InterM. M ± SEM	C Advan. M ± SEM	D InterF. M ± SEM	F
Board takeoff	$257 \pm 17^{b,c,d}$	363 ± 10^{a}	375 ± 11^{a}	327 ± 12^{a}	12.30**

Note. ^{a,b,c,d} indicate significant differences from group A, B, C, D. $p < 0.05$.

The results in Table 26 indicated:

1. The intermediate and advanced groups had significantly higher body angular velocities than the beginning group. The results of Duncan's Multiple Range Tests suggested that the beginning gymnasts had very slow body rotation at board takeoff.

2. No significant differences were noticed between the advanced and intermediate groups.

Correlation between the Center of Mass

Linear Velocity and Hurdle Length

The results in this study indicated that the horizontal and resultant velocity at the center of mass was based on the skill level. In addition, the advanced group also demonstrated a significantly longer hurdle distance than the beginning group. To examine whether there is a strong relationship between velocity and distance, this study calculated the correlation coefficient between the center of mass horizontal and resultant velocity at the hurdle foot touchdown, hurdle foot takeoff, and hurdle distance. The results are displayed in Table 27.

Table 27

Correlation Coefficients

between the Center of Mass Linear Velocity and Hurdle Length

R	Horizontal Hurdle foot touchdown	Horizontal Hurdle foot takeoff	Resultant Hurdle foot touchdown	Resultant Hurdle foot takeoff
Hurdle length	0.93**	0.91**	0.93**	0.92**

Note. ** $p < 0.01$.

The high correlation results in Table 27 confirm that the correlation between the hurdle distance and the center of mass horizontal and resultant velocity at the hurdle foot touchdown and hurdle foot takeoff was significant. The correlation coefficients also suggested that the faster a gymnast approaches the board, the longer the hurdle distance will be.

Hurdle Distance

Theoretically, the hurdle flight distance should be short in order to maintain the horizontal velocity obtained during the approach run and keep the velocity loss at a minimum. However, because of the requirement that at the hurdle foot takeoff a vaulter should reach or maintain the maximum horizontal velocity, the hurdle push-off leg must execute a powerful takeoff. In addition, because of the difference between the hurdle and normal sprinting, a vaulter has to adjust the movement of the arms and legs, bring both legs together, and land with both feet on the springboard in an appropriate body position. These differences imply that the time and distance of a hurdle flight will be longer than a normal sprinting stride. The results from this study showed that the average hurdle distance was 2.78 meters for the advanced group, 2.65 meters for the male intermediate group, 2.40 meters for the female intermediate group, and 1.84 meters for the beginning group. Compared to the average length of the last step, which was 1.09 meters, 1.40 meters, 1.51 meters, and 1.35 meters for the beginning, male intermediate, advanced, and female intermediate groups, respectively, it is apparent that the hurdle distance is much longer than the length of the last step. Duncan's Multiple Range Tests on the hurdle length between every two groups indicated that the difference was based on the level of performance. The less skilled vaulters had a significantly shorter hurdle length, while the advanced vaulters had a significantly longer hurdle distance than the less skilled vaulters. The significant correlation coefficient between the center of mass horizontal and resultant velocity and the hurdle distance (see Table 27) indicated that it is unrealistic for a fast-sprinting vaulter to finish the hurdle within a very short distance. It is also inappropriate to advise a beginning skill-level gymnast to try a very long hurdle. The average hurdle distance calculated in this study among the four different skill-level groups can serve as a reference for gymnastics instructors and coaches.

Body Position during the Hurdle and Board Takeoff

It is a fact that from the approach run to the hurdle step and board takeoff a vaulter's body segments will experience a series of transitional movements in order to get into the proper position for the board contact and board takeoff. However, how the body should be positioned has been controversial. The results from this study indicated no negative trunk movement from the hurdle foot touchdown to board takeoff among the four different groups. At the hurdle foot takeoff. the trunk position was almost straight with a slight forward lean between two to four degrees in general. During the hurdle step. the slight forward trunk-leaning position did not disappear. Rather. it became increased to approximately 24 degrees from the vertical line at the feet-together position. Though the average forward trunk-inclination reduced to about 20 degrees at board contact. the trunk forward-leaning position increased to 40 degrees at board takeoff. From a biomechanical point of view. the backward trunk movement will affect the center of mass horizontal velocity and reduce the ratio of horizontal velocity utilization. Therefore. the backward movement of the trunk is not a correct technique.

Meanwhile. the results of the body-forward lean did not imply that the more forward body inclination the better. as stated by Takei (1989). It is the author's opinion that the body position has to be set within a target zone where a vaulter can get the most possible reaction force from the springboard. The results from this study revealed that at board takeoff the advanced group had an average leg angle of 82.4 degrees. which was significantly less forward than the beginning and male intermediate groups.

Because the successful execution of the handspring group vaults requires proper horizontal. vertical. and angular velocity at board takeoff. the body position has to meet the three requirements at the same time. The board takeoff with a straight body position over the board. which has a very short distance from the center of mass to the vertical line of the board-reaction force. will result in better vertical velocity. but less horizontal and angular velocity. In this study. the female intermediate group had an average leg angular displacement of 50.5 degrees at the feet-together position. 54.7 degrees at board contact. and 83.6 degrees at board takeoff. Because of the smaller leg-blocking angles and a large takeoff angle. the female intermediate group also displayed significantly lower horizontal velocities at board takeoff. lower ratios of horizontal velocity utilization. and slower angular velocity of the body. Their average horizontal velocity for the center of mass was 3.31 meters per second at board takeoff. which was significantly less than the average of 4.26 meters per second for the male intermediate group. Their average ratio of horizontal velocity utilization was 0.54 at board takeoff. which was also significantly smaller than the 0.63 from the male intermediate group.

The board takeoff with greater body-forward inclination can reduce the horizontal velocity loss and resulted in better ratios of horizontal velocity utilization. At the same time. this body position will also produce a less powerful vertical velocity and less angular velocity. Though this kind of takeoff body position suggests a greater distance from the center of mass to the vertical line of board-reaction force. the actual board-reaction force on the legs will become significantly less because of the smaller takeoff angle of the legs. The significantly reduced vertical velocity will. in turn. affect the body angular velocity negatively. The author's observation of the 1994 World Gymnastics Championships men's compulsory vault. which does not require much vertical and angular momentum. confirmed that all of the world-class gymnasts took off from the board with a significant forward inclination of the body. Apparently. the technique of board takeoff with significant forward body inclination is suitable for the vaults that do not need much vertical and angular velocity at board takeoff.

The board takeoff with legs slightly past the board vertical line of reaction force and a significant trunk-forward inclination will be able to keep the horizontal velocity loss at a reasonable rate and utilize the board-reaction force efficiently at the same time. Because of the significant trunk-forward lean, a smooth and fast transition will occur in the preflight. In addition, this trunk-forward inclination will maximize the distance from the center of mass to the vertical line of board-reaction force. The outcome for the board takeoff with an almost vertical leg position and a significant trunk-forward inclination is likely the most appropriate horizontal, vertical, and angular velocity required for executing the handspring group vaults. Besides, this flexed board takeoff body position will enable a gymnast to obtain more potential for the fast and powerful swing of the legs in the preflight phase.

The Blocking Action of the Legs

Traditionally, the board takeoff has been considered a blocking action by bringing both feet in front of the center of mass when making board contact. In this way, the forward horizontal velocity will be blocked into three parts--horizontal, vertical, and angular velocity. However, the fast hurdle step does not automatically guarantee a powerful board takeoff with a desired horizontal, vertical, and angular velocity. How to put the most possible force on the springboard, cause the most possible board deflection, and generate the most possible board reaction force in the least amount of time are the questions to be answered.

A vaulter cannot alter the hurdle trajectory at the center of mass once the vaulter takes off from the runway. Because of the requirement of keeping the horizontal velocity loss at a minimum during the hurdle. the hurdle flight trajectory at the center of mass cannot be very high. Rather. it is supposed to be a low trajectory. Therefore. the question becomes how to get the increased vertical impact on the springboard while keeping a low hurdle flight trajectory. Though a vaulter cannot change the hurdle flight trajectory and the horizontal velocity at the center of mass during the hurdle. a vaulter can alter the vertical velocity on the springboard by the relative movement of body segments. A different leg movement can have a different impact on the springboard.

From the hurdle foot touchdown to the hurdle foot takeoff. the fast swing of the front free leg can significantly increase the velocity of the leg. The results from this study indicated that the advanced gymnasts had a very fast relative movement at the free-leg knee joint and the linear velocity at the knee joint was significantly faster than the less skilled gymnasts. After the hurdle foot takeoff. the front free leg tends to be stabilized. But the fast swing of the push-off leg after the hurdle foot takeoff can significantly increase the linear velocity of the leg. The results from this study also indicated that the advanced gymnasts showed significantly greater linear velocities than the less skilled gymnasts at the hurdle push-off leg knee and ankle joints.

To get the most possible impact on the springboard at board contact. the downward vertical velocity is apparently the most important technique. Any segmental movement that can increase the downward velocity will help the body get increased impact on the springboard. The fully flexed knee angle on the push-off leg means higher ankle position. Since the ankle possesses the greatest potential in the leg-movement chain. the increased height means a higher potential of energy. an increased range of relative movement. and an increased downward velocity on the lower legs. The difference of the two different knee flexion techniques on the push-off leg is obviously seen (see Figure 9).

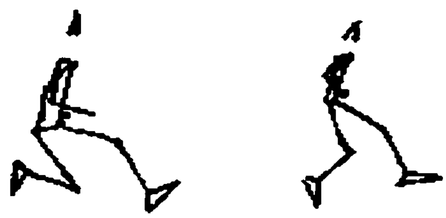


Figure 9. Two Different Knee-Flexion Techniques

The results from this study indicated that the advanced group had a greater knee flexion during the hurdle than the low-skilled group. The advanced group also showed a significantly greater downward vertical velocity at the ankle joint than the beginning group and female intermediate group. The frame by frame observation of videotapes of the 1994 World Gymnastics Championships in vaulting confirmed that the world-class gymnasts also went through small knee angular displacement on the hurdle push-off leg during the hurdle flight. Therefore, the fully flexed knee angle, the high ankle position, and the fast forward-and-downward swing of the ankle (foot) are apparently the advanced striking techniques.

The fast swing of the ankle of the hurdle push-off leg can increase its linear velocity. However, if the ankle stops its swing too early, the ankle will lose its relative movement. As a result, the increased benefit will disappear. Therefore, the fast swing of the ankle has to be continuous. This means that a vaulter should finish the feet-together position just a fraction of time before board contact. In other words, the shorter the time from the feet-together position to board contact. the better the impact will be. The results from this study confirmed the advanced striking theory and techniques. The advanced group had an average of 0.02 second from the feet-together position to board contact. which was significantly shorter than the average of 0.07 second from the beginning group from the instant of the feet-together position to board contact.

The active-board striking techniques do not just stop at the feet-together position. Unlike the traditional board-blocking techniques that treat the whole body as a rigid object before hitting the board. the advanced vaulters start their board striking from the feet-together position. The increased angular displacement at the knee. hip. and shoulder joints can be seen from the advanced vaulters. Because of this early active striking. the legs. especially the ankle. can keep the increased downward velocity continuously. Most important. this early and active board-hitting technique can change the direction of the horizontal velocity dramatically. As a result. a significantly increased downward impact on the springboard can be expected. Apparently. this active striking technique which focuses on the impact of the springboard has many advantages over the traditional blocking techniques. The board-blocking techniques tend to lose the horizontal velocity significantly and turn out a large vertical velocity and a low horizontal and angular velocity. The active board-striking technique puts its emphasis on getting the most board reaction force without significant horizontal velocity loss. The results from this study indicated that most of the advanced vaulters used the active striking techniques. In contrast. most of the beginning group utilized a passive board-takeoff technique. They had less knee flexion on the push-off leg in general during the hurdle flight and finished the feet-together position significantly earlier than the advanced group. Apparently, it is very appropriate to use the term **striking** instead of blocking for board takeoff.

Knee Flexion and Extension during

Board Takeoff

It has been widely believed that a vaulter will undergo slight knee flexion after board contact (Arnold & Stocks, 1979; Bowers et al., 1981; Cooper, 1980; Dolan, 1980; George, 1980; Hay, 1993; Schmid & Drury, 1977; Simalevski & Gerveldovski, 1979). The results from this study indicated that the knee flexion was basically based on the level of performance, with the beginning group having the greatest knee flexion, the male and female intermediate groups having moderate knee flexion, and the advanced group having an average of only 2.6 degrees of knee flexion. Some of the advanced vaulters showed no knee flexion during the board-takeoff period. The author believes that the no-knee-flexion technique is an advanced board-takeoff technique that requires strong and active leg-muscle involvement. The reason that the knee flexion before extension is a kind of less advanced technique is based on the theory that, after board contact, the flexion of the knee joints will cause the center of mass to undergo downward acceleration. This downward acceleration will bring out the upward force of inertia: $F = -ma$, assuming that the downward direction is positive. This upward force of inertia will reduce the impact force on the springboard and cause the unweighting of the board. The study by Kreighbaum (1974) has already verified this finding that the board underwent a maximal deflection, followed by a deep decrease because of knee flexion and then by a submaximal deflection. Since the submaximal board-reaction force is significantly less than the maximal force, the potential of getting increased board-reaction force is of great importance. By using the active striking technique and eliminating the knee flexion during board takeoff, there will be no upward force of inertia. As a result, the reaction force a vaulter can get will be the real maximal reaction force and the most possible takeoff momentum.

Board Contact Time

Previous studies on the board contact time have been controversial. The results from this study indicated that the advanced group had an average of 0.1 second on the board, which was significantly less than the beginning skill-level groups. This result was consistent with the studies by Bruggemann (1987), Kreighbaum (1974), Ou (1980), and Nelson et al. (1985). But this finding was contradictory to the studies by Takei (1988, 1989) and Takei and Kim (1990).

It is the author's opinion that the advanced board-takeoff technique will take significantly less time than using less advanced techniques adopted mostly by the less skilled gymnasts. To better understand whether the board-contact time should be long or short, we need to understand why the vaulters need a springboard. The purpose of using a springboard is to be able to obtain a powerful takeoff momentum that can meet the vaulting requirements for the horizontal, vertical, and angular momentum.

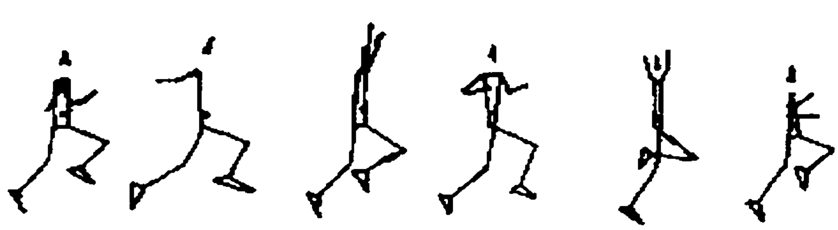
In order to obtain a powerful board takeoff, a gymnast must try to strike the board very hard in order to cause the most possible board deflection and to secure the most possible rebounding force from the board. Knee flexion, which can increase the time on board and decrease the reaction force from the board, has been proven to be a less advanced takeoff technique. In addition. according to the impulse momentum relationship formula

$$Ft = mv_f - mv_i$$

if the change of momentum (mv_f - mv_i) is known. for example. the momentum at board contact and board takeoff in this study can be calculated and then the impulse (Ft) can be known. The shorter the time. the greater the force will be. In other words. the longer the time. the less the force will be. Since it is the impact force and the time that cause the board deflection and reaction. the shorter time on the board means an increased impact force: and. vice versa. a longer time on the board will result in less reaction force from the board. Apparently. only the short time and a powerful impact force can produce a fast board-takeoff momentum. In addition. a longer time on the board will cause significant horizontal velocity loss. Therefore. it is impossible for a vaulter who has a very fast hurdle. active board contact. and significant takeoff momentum to come out with a significantly longer time on the board. The study results that concluded that advanced gymnasts had a longer time on the board may be caused by an error during the filming or digitizing process. The examination of Takei's (1991) study. which supported the longer board-contact theory. indicated that the camera. which was placed at 78.14 degrees to the vertical direction and far away from the movement plane. was set inappropriately. Under this circumstance. it is very difficult to get clear and accurate pictures so that the digitizer can see the actual start of feet contact and takeoff from the board.

Advanced Arm-Movement Styles

In this study, six different arm-movement styles were found. Gymnastics teachers and coaches are interested to know which style is more technically advanced than the others. To answer this question, the purpose of the arm movement during the hurdle and board takeoff has to be clear. It is the author's opinion that the arm movement should serve the following four requirements: (1) to help maintain the fast horizontal velocity with as little speed loss as possible during the hurdle, (2) to help body segments obtain a smooth transition from the hurdle to board contact, (3) to help the whole body get the most possible impact on the board, and (4) to help the whole body get the most possible momentum that is appropriate for the specific vaulting movements at board takeoff. Apparently, the arm- movement style that can serve all four requirements will definitely be the most advanced arm-movement style. First, this study compared the (1) natural sprinting style, (2) straight arm-swing style, (3) big sideways circling style, (4) small sideways circling style, (5) hands up-and-down style, and (6) hands reaching forward style at the hurdle foot takeoff (see Figure 10).



(1) (2) (3) (4) (5) (6)

Figure 10. Six Different Arm-Movement Styles at the Hurdle Foot Takeoff

In responding to the assistance of the arms in maintaining the fast horizontal velocity, the answer is very clear that the natural sprinting style is the best posture for maintaining the fast horizontal velocity during the approach run. The study and practice in track and field have already proven that the natural sprinting style is the best posture for balancing the sideward-and-backward rotation of the body caused by the fast forward-and-upward swing of the front knee. In addition, the fast forward-and-upward swing of the front arm can increase the inertia force on the ground and cause the increased reaction force.

The straight arm-swing style has a little weakness in maintaining the horizontal velocity. At the hurdle foot takeoff, the backward position of the arms can prevent the backward rotation of the body. However, this style cannot help the push-off leg get the most powerful hurdle takeoff.

In regard to the big sideways circling style, the upward-and-sideward position of the arms cannot prevent a slight backward lean of the torso caused by the fast forward-and-upward swing of the front knee. Because the arms are in a relatively high position, the center of mass will also be a little higher than the normal sprinting position. This relatively high position of the center of mass will cause the reaction force from the ground to the center of mass to be a little higher, which in turn will cause a higher hurdle flight trajectory. In this study, the advanced group had three vaulters (50 percent) using the big sideways circling style. The average hurdle flight angle was 11 degrees, which was a little higher than the advanced target range of six to nine degrees offered by Simalevski and Gerveldovski (1979).

With regard to the small sideways circling style, hands up-and-down style, and hands reaching-forward style, it is obvious that the position of the arms at the hurdle takeoff cannot help balancing the slight sideward-and-backward rotation of the body and, consequently, has no benefit for a strong hurdle leg push-off.

In responding to the assistance from the arms for a smooth transition during the hurdle, the straight swing style is apparently the best and the easiest. The arm movement in this style just involves a straight forward-and-upward swing, which moves the same direction as the center of mass does. The hands reaching-forward style is also easy to keep during the hurdle. The natural sprinting style requires certain coordination between the two arms. After the hurdle takeoff, the front hand needs to go back down and the back hand needs to move down and forward and then both hands start to swing forward and upward from the sides. Obviously, the natural sprinting style can also help the whole body get a smooth transition during the hurdle if the vaulter can coordinate his or her arms efficiently. For the big and small sideways circling styles, because of the circling swing, the arms will go through different places. This circling arm movement can affect the smooth distribution of the center of mass. In addition, the circling swing can cause the shoulder and torso to undergo a relative backward-and-forward motion and, as a result, affect the smooth transition at the center of mass. The hands up-and-down style can also affect the smooth distribution of the mass center. The sudden downward movement of the hands can also cause the forward lean of the shoulder and decrease the angular displacement of the hip and shoulder joints at board contact. This study has already revealed the fact that the advanced vaulters had increased angular displacement at the shoulder, hip, and knee joints before board contact. The reverse movement caused by the hands up-and-down style is apparently a poor technique.

In regard to the assistance of the arms for the most possible impact on the board, the straight arm-swing style is obviously the best way to get the most possible impact on the board. Since this arm-movement style starts its arm swing while the hands are behind the body, this long range of motion makes it possible to get the maximal angular velocity at the shoulder joint and the greater linear velocity at the wrist during board contact. The maximal forward-and-upward swing of the arms can increase the inertia force on the board, cause more board deflection, and get more board reaction. The results from the pilot study about an advanced vaulter who used the straight arm-swing style indicated that the angular velocity at the shoulder joint reached 1,055 degrees per second and the linear velocity at the wrist joint recorded 15.65 meters per second at board contact, which was apparently much greater than the average of 482 degrees per second on the angular velocity of the shoulder joint and greater than the average 8.84 meters per second on the linear velocity at the wrist joint from the advanced group.

The natural sprinting style usually starts the straight forward-and-upward arms swing when both hands are next to the hips. Therefore, the range of the arm swing of this style is less than that of the straight arm-swing style. This difference of motion range means that the natural sprinting style will have a little less momentum on the arms than the straight arm-swing style.

The big sideways circling swing style, according to this study, finishes the hands-together position around the sides of the body and then starts the forward-and-upward swings in most cases. In addition, because of the sideways circling swing, the direction of the arm swing is not always straight. Therefore, this arm-movement style generally has the same potential as the straight arm-swing style does.

The small sideways circling swing style, because the arms are always in a flexed position, will have significantly less shoulder angular velocity and wrist linear velocity at the instant of board contact. The result is obviously less momentum on the arms. In this study, the advanced group had three gymnasts (50 percent) using the small sideways circling swing style and three gymnasts (50 percent) using the big sideways circling swing style. The male intermediate group used the natural sprinting and the big sideways circling swing styles. The results from this study indicated that the male intermediate group had better shoulder angular velocity and wrist linear velocity at the instant of board contact than the advanced group.

The hands up-and-down style and the hands reaching-forward styles are clearly the wrong arm-swing techniques because of no forward-and-upward swing of the arms. The downward swing of the arms can reduce the board impact by reducing the inertia force on the board.

In regard to the assistance of the arms in getting the most possible horizontal and vertical velocity at board takeoff, the results from this study indicated that the advanced group had a significantly faster horizontal velocity at the wrist joint than the less skilled groups. This finding suggests that, at the end of board takeoff, the fast-reaching forward movement of the hands is of significant importance in keeping the horizontal velocity and reducing the time of preflight. To get the most possible vertical velocity at board takeoff, the arms need a fast upward swing from the feet-together position to board contact. Then, at board takeoff, the upward swing of the arms stops. In this study, the advanced group had the highest vertical velocity on the wrist joint at the instant of board contact; and at the instant of board takeoff, the wrist vertical velocity was reduced to almost zero. Apparently, all of the six different arm-movement styles can stop the upward vertical velocity of the hands and quickly reach the hands forward at the instant of board takeoff.

By reviewing the six different arm-movement styles, as well as their compliance with the requirements of the advanced arm movement during the hurdle and board takeoff, the answer of the advanced arm-swing techniques is obvious. The natural sprinting style is the only one that can meet all four requirements. The biggest advantage of the natural sprinting style is its maintaining of the fast horizontal momentum at the hurdle foot takeoff. Though the natural sprinting style may not be able to compete with the straight arm-swing style on the arms' momentum, the increased horizontal momentum at the center of mass will mean an increased impact on the springboard.

The second advanced arm-movement style apparently is the straight arm-swing style. It can serve three of the four requirements for the advanced arm movement very well. The greatest advantage of the straight arm-swing style is its fast arm momentum and smooth transition. None of the other four arm-movement styles can meet more than two requirements of the advanced arm swing. Therefore, those four arm-movement styles (big sideways circling swing style, small sideways circling swing style, hands up-and-down style, and no arm-swing style) should not be encouraged by gymnastics instructors and coaches during the vaulting practice.

The advanced arm-swing techniques confirmed in this study have been proven to be the correct answer. A videotape survey of China's and Russia's gymnastics teams who were the first and second place, respectively, in the 1994 World Gymnastics Championships during the men's team competition indicated that the natural sprinting technique was the most popular arm-movement style used by the world's best gymnasts. The second popular arm-movement style was the straight arm-swing technique. Only one gymnast of the two teams was found using the big sideways circling swing style during the vaulting competition. In addition, those who performed the highest difficulty vault--handspring and double-front somersault--used the natural sprinting style only in this competition. Also, a report by He and Shang (1993) indicated that Chinese gymnasts performed the handspring and double-front somersault with the straight arm-swing technique.

In comparison, the observation of the United States men's gymnastics team during the vaulting competition of the 1994 World Gymnastics Championships indicated that none of the six vaulters used the natural sprinting arm-movement technique. Only one gymnast used the straight arm-swing technique; three of the six vaulters adopted the big sideways circling swing style; and two team members used the small sideways circling swing style. The wide use of the less advanced arm-swing techniques may be one of the reasons for the ninth-place standing of the team during this event.

Advanced Hurdle and Board Takeoff Techniques

One of the purposes of this study was to provide gymnastics instructors and coaches with detailed and clear information about the advanced hurdle and board-takeoff techniques. By comparing and analyzing the general, as well as the detailed, kinematic features among the different skill-level gymnasts, the whole picture of the advanced hurdle and board-takeoff techniques has become clear.

The advanced hurdle and board-takeoff techniques not only feature the fast horizontal velocity at the center of mass during the hurdle and takeoff from the board, but also demonstrate the significant efficiency of using the horizontal momentum by a higher ratio of horizontal velocity utilization. The high efficiency of utilizing the horizontal velocity is shown by a low leg-takeoff angle, a lower vertical velocity on the center of mass, a low hurdle flight angle, a fast swing of the front free leg, a strong push-off by the hurdle leg, and an advanced arm-swing style by using the natural sprinting style or the straight arm-swing style at the instant of hurdle foot takeoff.

During the hurdle, the advanced hurdle trajectory tends to be low and fast, even though the hurdle distance is longer than the less skilled vaulters. The hurdle push-off leg is actively involved during the hurdle period. Specifically, the knee starts its fast-forward swing first along the fully flexed knee angle. The ankle, which is located in a relatively high position, then starts the explosive downward-and-forward striking. The active striking also features a very late feet-together position. The time from the feet-together position to board contact is so short (0.01 second) that a vaulter should feel that the feet-together position means board contact. There should be no passive waiting period before board contact. Another feature of the advanced hurdle and board-takeoff techniques is the whole body's active striking. The fast extension of the knees. hips. and shoulders starts before board contact instead of after board contact. The arms are also actively involved by the fast forward-and-upward swing, and the hands should reach the maximal vertical velocity at the instant of board contact.

During the board contact phase. the advanced board-takeoff technique involves no knee flexion. With just a very short period of withholding while the board gets its maximal deflection. the knees start the forceful extension. For a vaulter. the powerful board striking should be as quick as possible. No knee flexion or withholding should be felt. Also. during board takeoff. the arms. trunk. and legs should be well coordinated by showing a brief synchronized linear velocity increase at the wrist. shoulder. hip. and knee joints. Because of using the active board-striking technique. the board contact time should be significantly less than the passive blocking techniques.

At board takeoff. the advanced vaulter will show steady or increased angular velocity at the hip joint. In addition. the body segments at the wrist. shoulder. hip. and knee joints should demonstrate increased linear velocity at board takeoff. The hands should be at about the head level with fast horizontal velocity and zero vertical velocity at board takeoff. This means that the hands should quickly reach forward for the horse contact and reduce the preflight time. The position of the legs at board takeoff should be slightly over the vertical line of the board-reaction force (82.4 degrees). The trunk should have a forward inclination at about 40 degrees. In conclusion. the advanced hurdle and board-takeoff techniques should provide the vaulter with the potential for the more powerful board takeoff that can generate the necessary horizontal, vertical, and angular momentum for the successful execution of the entire vault.

CHAPTER 5

Summary, Conclusions, Recommendations, and Implications

Summary

The redefined definition of movement techniques, as well as the detailed analysis, which for the first time focused on the relative movement of body segments and their coordination during the performance, apparently opened a new direction for gymnastics movement analysis. This clear and detailed research also provides gymnastics instructors and coaches with a better understanding about the advanced hurdle and board-takeoff techniques, which in turn will directly promote the development of gymnastics. In addition, the three-dimensional analysis of the hurdle and board takeoff among the four different skill-level groups also revealed the following:

1. The advanced gymnasts not only had significantly faster horizontal and resultant velocities than the less skilled gymnasts during the hurdle and board takeoff, but also presented better ratios of horizontal velocity utilization. The efficiency of horizontal velocity utilization was partially indicated by a significantly lower vertical velocity at the hurdle foot takeoff, a lower hurdle flight angle, and a lower hurdle flight height.

2. Compared to the distance of the last step, the hurdle distance was much longer. The advanced vaulter had an average of 2.78 meters on the hurdle length, which was significantly longer than the less skilled gymnasts. Yet the longer hurdle distance was finished with significantly faster hurdle flight time.

3. The advanced gymnasts took off from the board with an average leg angular

displacement at 82.4 degrees, and an average trunk-forward inclination at 40 degrees. The leg-forward lean was significantly less than the beginning and male intermediate gymnasts. The technique differences were important factors for advanced gymnasts to takeoff from the board with a significantly higher vertical velocity, while still maintaining a fast horizontal velocity.

4. The advanced gymnasts had a significantly faster relative movement of the body segments than the less skilled gymnasts. The fast relative movement was indicated by the fast swing of the front free leg from the hurdle foot touchdown to the hurdle foot takeoff, by the fast swing of the hurdle push-off leg during the hurdle, and by the fast swing of both arms during the hurdle and board takeoff.

5. The advanced gymnasts showed a significantly better timing technique on the legs. The time difference from the instant of feet together to the board contact, for example, was only 0.02 second on average, which was significantly shorter than the low-skilled gymnasts.

6. The advanced gymnasts angled their arms differently during the feet-together position to board takeoff. At board contact, the advanced gymnasts had an average of 107 degrees, which was significantly larger than the beginning gymnasts, who averaged 41 degrees. At board takeoff, the advanced gymnasts showed an average angular displacement of 134 degrees at the shoulder joints, which was also significantly larger than the low-skilled vaulters, who averaged 110 degrees.

7. The advanced gymnasts involved their arms more actively during the hurdle and board takeoff. Their average maximal linear velocity at the wrists was significantly faster

than the low-skilled gymnasts.

8. Six different arm-movement styles were identified in this study. The "natural sprinting style" and the "straight swing style" were identified as the advanced arm-swing techniques. In comparison, none of the advanced gymnasts in this study used the advanced arm movement techniques.

9. The segmental coordination analysis on the angular velocity at the knee, hip, and shoulder joints among the four different skill-level groups indicated that the angular velocity at the hip and shoulder joints tended to increase from the feet-together position to board contact. During the board contact, the advanced gymnasts generally had fewer changes on the angular velocity of the knee, hip, and shoulder joints. At board takeoff, most of the advanced gymnasts demonstrated increased angular velocities at the hip joint.

10. The segmental coordination analysis on the linear velocity at the wrist, shoulder, hip, and knee joints among the advanced gymnasts indicated that, from the feet-together position to board contact, the linear velocity at the wrist and shoulder joints tended to decrease, while the linear velocity at the hip and knee joints increased. From the board contact to board takeoff, the advanced gymnasts displayed a simple and smooth transition on the linear velocity at the wrist, shoulder, hip, and knee joints. The advanced gymnasts generally presented more synchronized increases on the linear velocity at the wrist, shoulder, hip, and knee joints than the low-skilled gymnasts.

11. The analysis of body angular velocity at board takeoff indicated that the advanced gymnasts had an average body angular velocity of 375 degrees per second, which was significantly faster than the low-skilled gymnasts.

12. The advanced gymnasts had an average board contact time of 0.1 second, which was significantly shorter than what the low-skilled gymnasts had.

Conclusions

Based on the results from this study, it was concluded that there was a significant difference in the way of performing the hurdle and board-takeoff movements among the different skill-level groups. The difference was distinguished by the relative movement of body segments and their coordination in a specific time. The advanced gymnasts generally involved their arms, trunk, and legs more actively, more efficiently, and with better timing and coordination among the body segments. The result was that after board takeoff the advanced gymnasts were able to exert the necessary horizontal, vertical, and angular velocity required for successful vaulting.

Recommendations for Future Research

First, this study explored the general and detailed kinematic features of performing the hurdle and board takeoff among the different skill-level gymnasts. However, this study is only part of the comprehensive study. The kinetic experiment that focuses on the interaction between the gymnasts and the springboard is needed. Though a couple of kinetic studies have been conducted by Kreighbaum in 1974 and 1979 regarding the kinetic features of the board takeoff, the limited subjects, different board, and different techniques used during that time have made further study necessary. In addition to studying the interaction between the vaulter and the springboard, future studies also need to examine the impact on the board by the different arm-movement styles and the different leg-striking techniques. In this way, gymnasts teachers and coaches will have a better understanding about board contact and takeoff techniques.

Second, this study involved subjects who ranged from the beginning skill level to the advanced national level. Though some observation on the performance of the hurdle and board-takeoff techniques was done at the world-class elite level, detailed kinematic and kinetic studies are still needed to completely clear the misconception and set up models for the national-level gymnasts.

Third, this study involved the intermediate skill-level female gymnasts only. Comprehensive kinematic and kinetic studies on the female gymnasts at different skill levels are needed.

Implications for Teaching

Based on the results of this study, the following information regarding the hurdle and board-takeoff techniques can be taught to gymnasts.

1. The hurdle step should be treated as part of continuous sprinting. This means that there should be no slowdown after the hurdle foot takeoff.

2. At the hurdle foot takeoff, the hurdle push-off leg should be at about 62 degrees. A greater hurdle takeoff angle will mean higher vertical velocity at the hurdle takeoff, which in turn will cause more horizontal velocity loss.

3. The last step for the advanced gymnasts should be about 1.51 meters. Beginning gymnasts who have a slower horizontal velocity should have a shorter distance.

4. The hurdle distance for the advanced gymnasts should be around 2.78 meters. Because the hurdle distance is closely correlated with the center of mass horizontal velocity, the slower the horizontal velocity, the shorter the hurdle length should be.

5. The hurdle flight time should be 0.24 second for the advanced gymnasts. The general rule for the hurdle time is "the faster, the better."

6. The hurdle flight height should be about 0.11 meters for the advanced gymnasts. The higher hurdle flight height will result in longer hurdle flight time.

7. The hurdle flight angle at the center of mass should be around 11 degrees. The higher hurdle flight angle will mean more horizontal velocity loss.

8. The board takeoff angle should be about 82.4 degrees for the legs and 40 degrees for the trunk when performing handspring vaults.

9. The board contact time should be 0.1 second for the advanced gymnasts. The low-skilled vaulters tend to have longer time on the board. They should be taught that the board takeoff should be very short and powerful.

10. After the hurdle foot takeoff, the push-off leg should undergo a series of fast relative movements. The first quick relative movement is the fast swing of the knee, followed by the fast knee-flexion and extension movement. This means that the lower leg should be actively involved during the board striking.

11. The time from the instant of the feet-together position to board contact should be very short. The advanced gymnasts had an average of only 0.02 second.

12. During board contact, the average knee flexion for the advanced gymnasts was 2.6 degrees. Some advanced vaulters showed no knee flexion at all. Therefore, gymnasts should be taught that the active board striking, not the blocking, starts before board contact. During the board contact, the less knee flexion, the better board takeoff there will be. The board takeoff should be felt as a very short, powerful, and continuous extension of the leg

muscles.

13. Gymnasts should be taught to adopt the "natural sprinting style" or the "straight swing style" arm-movement techniques.

14. At the instant of board takeoff, the hands should quickly reach forward to reduce the horizontal velocity loss.

15. Gymnasts should be taught that a powerful board takeoff does not just come from strong leg-muscle involvement alone. As a matter of fact, a powerful board takeoff needs good coordination from the arms, trunk, and legs. It often means a simple and smooth transition of the angular and linear velocity from the body segments.

APPENDICES

APPENDIX A

MIDDLE TENNESSEE STATE UNIVERSITY

HUMAN SUBJECT COMMITTEE APPROVAL

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MIDDLE TENNESSEE STATE UNIVERSITY

HUMAN SUBJECT COMMITTEE APPROVAL

To: Mr. Taiyong Cao and Dr. Powell D. McClellan

From: Jwa Kim
Representative of College of Education
MTSU IRB

Re: "3-D Kinematic Analysis of Hurdle Step and Related Techniques in Performing a Forward Handspring Vault"
(Protocol Number: 95124ED)

Date: May 16, 1995

Since your research will be conducted in a established educational setting, it is approved according to 45 CFR Part 46. This approval is granted for one year only and must be reviewed by the committee on an annual basis if the project continues beyond the next 12 months; likewise any changes in the protocol require resubmission of your project for the committee approval. Best of luck on the successful completion of your project.

APPENDIX B

INFORMED CONSENT FORM

APPENDIX B

INFORMED CONSENT FORM

Explanation of Testing Procedures

The purpose of the study is to investigate detailed kinematic and technical differences between advanced and less advanced gymnasts on the hurdle step and board takeoff of forward handspring vaults. You will be videotaped two times of executing your normal forward handspring vaults.

Risks and Discomforts

"Minimum Risks" are included and are similar in magnitude to those encountered during your normal practice.

Freedom of Consent

Your participation in this test is voluntary. You are free to terminate participation at any time. You will not be identified personally at any time during the study and all the video tapes will only be used for the purpose of this study. The investigator will retain custody of the video tapes during the study. Once the study is completed a copy of the tapes will be filed with the dissertation in the HPERS Department of Middle Tennessee State university.

Consent to Participate

I hereby acknowledge that I have read this form in its entirety and that I understand the conditions of the test and the condition of my voluntary participation. I consent to participate in the test.

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Signature Date

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