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Departments of Bioengineering and Kinesiology

THE EFFECT OF HURDLE LENGTH AND FREQUENCY OF OSCILLATIONS ON HEIGHT AND RATE OF ROTATIONS IN DIVING

ILANA J. ZEISES

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The thesis of Ilana Zeises was reviewed and approved* by the following:

Dr. Vladimir Zatsiorsky
Professor of Kinesiology
Thesis Supervisor

Dr. Jaebum Park
Post Doctorial Scholar
Thesis Supervisor

Dr. Peter Butler
Associate Professor of Bioengineering
Honors Advisor

Dr. Stephen Piazza
Associate Professor of Kinesiology and Mechanical Engineering
Honors Advisor

*Signatures are on file in the Schreyer Honors College

ABSTRACT

Diving is a very unique sport. Many different athletes performing the same dive start that dive differently. This study questions whether the approach to starting a dive can affect the ultimate outcome of the dive. There is no agreed upon way to start a dive and so usually it is based upon the preference of the athlete or the coach. A hurdle is considered a forward approach in diving. It consists of a step, lifting the opposite leg, landing with the feet together, and swinging the arms backwards while jumping off. A back press is the backward approach. In order to perform a back press, a diver stands backwards at the end of the board with only the balls of his feet on the board and his heels hanging off the end. The diver may then oscillate the board by lifting and lowering his heels. When the diver is ready to take off he circles his arms backwards and jumps off. Both the hurdle and the back press are important in determining the final outcome of the dive. Momentum is conserved, thus while in motion, the diver will use any momentum gained in the takeoff. It is the positioning of the diver that will dictate how or in what direction that momentum will be used. Ideally, the diver should use the momentum to jump almost completely vertical. This study examines the aspects of both the forward and backward take offs. Using a video camera, it is tested whether or not the length of the step in the hurdle or the number of oscillations in a back press has a significant effect on the dive. The features of the dive being tested are the maximum height reached and the rate of rotation. Data for these variables are collected with the program KWON3D and statistical analysis is done using a ANOVA. Despite a lack of strong statistical significance, qualitative analysis shows that the middle hurdle length and the middle number of oscillations were the best options as the subjects jumped higher and spun faster. It is also shown that the varying hurdle lengths and oscillations do not result in a measurable difference in momentum.

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Chapter 1

Introduction

1.1 Introduction

Diving is a very individualized sport where many techniques are left up to the athlete's preference. The forward and backward approaches vary greatly depending on the athlete. Many times the athlete chooses an approach based on simplicity, comfort, or coach's preference. However, it would be ideal for an athlete to choose an approach that would increase his height or rate of rotation so that he may have more time to complete the dive. Using an approach that will generate momentum will aid the diver if the diver is in the correct upright position as he will have the correct trajectory leaving the board. The momentum gained in the hurdle will be conserved throughout the dive (Hamill, 1986).

The forward approach consists of a step, lifting the opposite leg, jumping to the end of the board, circling the arms backwards, and jumping off. During the step the board begins to compress downwards. The length of the step determines how much force the diver has against the board and thus how much the board will depress. When the diver jumps off the board, momentum is transferred back to the diver. Therefore, the more momentum gained from the first step, the more momentum the diver has for the dive. It is also important that the diver is upright so that the diver jumps vertically rather than horizontally.

In backwards approach the diver oscillating the board by raising and lowering the heels, circling the arms backwards, and jumping off. As the diver continues to oscillate the board kinetic energy is gained. The number of oscillations is based on the preference of the diver. A small amount of oscillations may lead to a small amount of energy. However, a large number of oscillations may lead to a loss of balance.

Gaining kinetic energy and therefore a greater height and rate of rotation is important in completing a successful dive. The higher the diver gets, and the faster the diver spins, the more rotations the diver can complete in less time. The diver will also be able to complete the dive sooner allowing more time to perfect the entry. Completing the dive at a greater height and entering the water cleanly are the major components of the sport of diving.

The goal of each dive is to get the highest score possible from the judges. Although, the judge is judging the entire dive, it is the entry into the water that makes the most impact on the score. The judge is looking for an entry in which the diver is completely vertical and does not create any splash. The elimination of the splash is done by the diver using his hands in order to create a hole in the top of the water. This technique is called ripping and it normally is accompanied by a loud slapping sound. In order to rip, the diver must have time to grab his hands and turn his palm towards the water. An excess of time between finishing the dive and entering the water is also impressive to the judges. Therefore, using a technique which will allow the diver to finish the dive higher and faster will lead to higher scores on each dive.

1.2 Purpose

The purpose if this study was to determine if height or rate of rotation achieved in a dive can be affected by the length of a forward hurdle or the number of oscillations in a back press.

1.3 Study Overview

A group of three elite divers were recruited for this study. All of the divers were members of the Penn State varsity diving team. Before the experiment, each diver had his or her own unique forward hurdle length and number of oscillations in the back press. Using marked lengths for hurdles and preset number of oscillations, the differences in height and rate of rotation for each trial were assessed.

1.4 Hypothesis

The hypothesis is that the length of the hurdle and the number of oscillations will increase both the height gained and the rate of rotation. For the forward hurdle, a middle hurdle length will be the most comfortable stride length for the subjects, and thus will allow the subject to generate the greatest amount of force into the board in a comfortable upright position. More force into the board translates into a higher and faster spinning dive. For the backward press, as the subject oscillates the board he will gain more kinetic energy and more momentum. However, the more he oscillates the board he may also lose balance. Thus the middle numbers of oscillations will also be the best choice because it will allow for the greatest combination of energy and balance.

1.5 Thesis Structure

Chapter 2 is a review of literature that is relevant to springboard diving. The methods used to perform the study are described in this study are in chapter 3. The results of each experiment are presented in chapter 4. Chapter 5 is a conclusion to the thesis that reviews the results, discusses possible future studies, and has final conclusions.

Chapter 2

Literature Review

2.1 Overview

This chapter is composed of four sections, which effectively describe topics relevant to this thesis. The sections include the basic concepts of diving, the biomechanics of diving, modeling methods of diving, and a summary of the chapter.

2.2 Basic Concepts of Diving

This section describes the basic actions and techniques performed by a competitive diver. The different subsections cover different categories of diving such as platform versus springboard, the forward hurdle, the back press, and direction of takeoff.

2.2.1 Platform versus Springboard

There are two different types of competitive diving. Platform diving consists of the diver jumping off a solid concrete tower 5m, 7.5m, or 10m above the water. Since the tower is made of concrete it has little give. Platform diving at the higher levels is generally reserved for older athletes, as a diver will hit the water from 10m at a speed of 16.4m/s (Rubin, 1999). Hitting the water at these speeds could lead to serious injuries if the diver is not prepared to hit the water. Springboard diving is performed at either 1m or 3m above the water's surface. A springboard is composed of aluminum and is generally 16ft long (Duraflex, 2003-2008). The diving board sits on a metal stand with one end attached and the middle of the board resting on a moving fulcrum. The track for the fulcrum begins 1.588m away from the bolted end of the board and continues for .584m

(Duraflex, 2003-2008). If the fulcrum is moved towards the bolted end then more of the board is able to bend and thus the diver will feel as the board has more spring. Conversely, if the fulcrum is moved towards the open end of the board, less of the board will be able to bend. The board will seem tighter to the diver and will not project the diver as high or as far into the air. A greater number and range of ages of athletes perform springboard diving than platform diving. A diver's speed entering the water from 1m is 8.4m/s, which is almost half the speed from 10m (Rubin, 1999). The following hurdles and presses discussed in this study apply only to the springboard and not to the platform.

2.2.2 The Forward Hurdle

In order to perform a forward dive, a diver must first complete a forward hurdle. The hurdle consists of a number of steps followed by lifting one's knee and arms, jumping to the end and circling one's arms backwards. The number of steps taken is determined by the foot that the athlete chooses to start the hurdle and the knee that the athlete chooses to lift in the hurdle (O'Brien, 2003). The hurdle becomes very personalized. The number, length, and speed of the steps depend on the individual athlete. The most important step is the last step as it sets up the body position for the rest of the hurdle. There is controversy over whether this step should be short or long to provide the maximum height.

2.2.3 Direction of Takeoff

Divers may leave the diving board in any of four directions. The most basic direction is the forward direction. To perform the forward direction the diver performs the forward hurdle and then completes a forward dive or somersault. Another basic direction is backwards. The diver performs a back press and then completes a backwards dive or somersault. The reverse direction is slightly more complex. The diver must complete a forward hurdle and then perform either a back dive or somersault flipping backwards towards the board. The final direction is the inward direction and it is similar to reverse. The diver performs a back press and then flips forward towards the board. The directions of the dives and the relationships between them are depicted in figure 2-1.

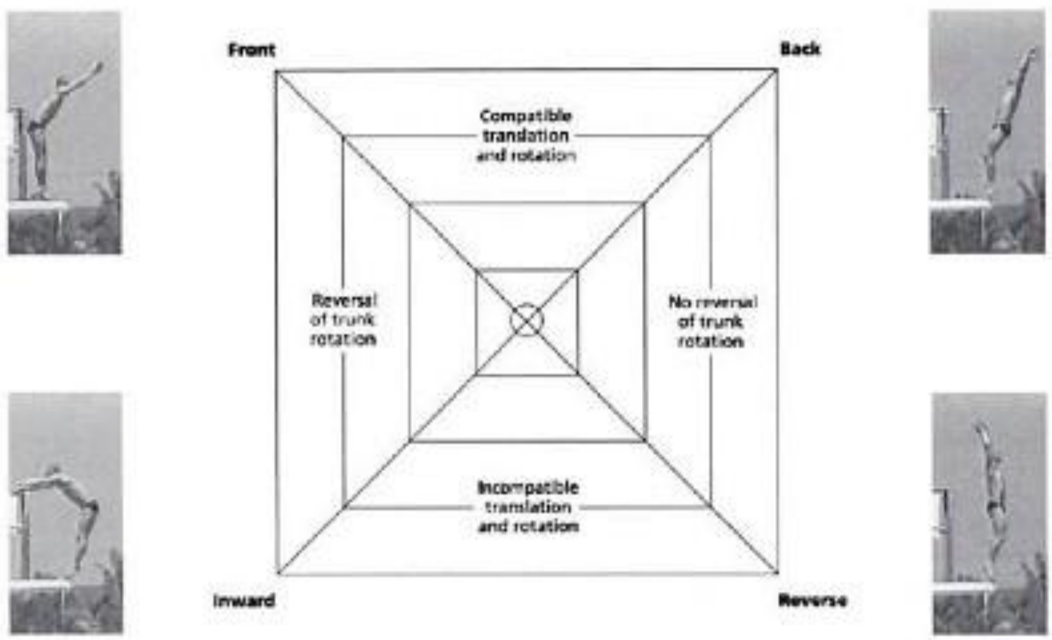

Figure **2-1**: Directions and relationships of dives (O'Brien, 2003)

2.3 Biomechanics of Diving

The section is composed of three subsections describing the biomechanics of diving at three different stages of the dive. The three stages are on the diving board, the take off, and in the air.

2.3.1 On the Diving Board

On the diving board refers on when the diver is still stable on the board, but preparing to jump off. Diving is a sport that is highly composed of physics. The simplest of ideas relating diving to physics is Newton's third law, for every action there is an equal and opposite reaction (Zatsiorsky, 2000). Thus the height the diver obtains in the air is directly related to the force the diver has pushing against the board. The diver can utilize the fulcrum to gain more of an upward force. In a study of jumping off diving boards in was found that, as predicted, the greater the compliance of the diving board, the greater the diver's height (Batterman, 1968).

2.3.2 The Takeoff

The takeoff is defined as when the diver is about to actually leave the board. A diver typically jumps off the board and begins to rotate. In order to continue to rotate the diver must have angular momentum. Angular momentum is obtained as the diver leaves the board and cannot be altered while in the air (Zatsiorsky, 2000). Thus, the amount a diver can spin in the air is a direct result of what occurs on the diving board (Zatsiorsky, 2000). Both the arms and legs are responsible for gaining momentum. However, in a study performed by Batterman in 1986 it was proven that, as the amount of intended rotations increases, the percent of the contribution of the legs towards momentum and the contribution of arms towards momentum are exchanged. Generally the study found that the percent of momentum contribution from the arms increased while the percent from the legs decreased; however, there are still some variations between the amounts of the changes (Batterman, 1968). For an average dive, about one third of the momentum is gained by the arms (Hamill, 1986). The harder a diver throws his arms down, the more momentum he will gain (Frohlich, 1978). It has been questioned by Frohlich whether divers violate the laws of angular momentum, because divers can jump into the air with seemingly no momentum and then complete a somersault. However a paper by Frohlich demonstrated that the momentum from rotation comes from the diver throwing his arms down and therefore the angular rotation of the somersault comes from the angular rotation of the arms. Figure 2-2 shows how a diver gains momentum for both forward and backwards somersaults.

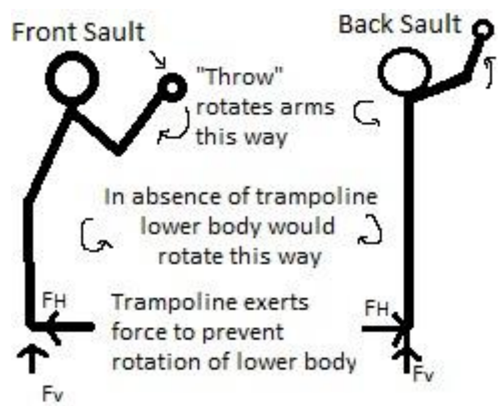

Figure **2-2**: Initiation of somersaults by gaining momentum (adapted from (Yeadon, 2006))

2.3.3 In the Air

The time in the air is when angular velocity is considered. Unlike angular momentum, a diver can change his angular velocity. This is because angular velocity is also dependent upon the moment of inertia (Zatsiorsky, 2000). The moment of inertia maybe calculated using the mas, length, and radius of the object. The angular velocity is the speed that the diver flips in the air and therefore it is a common term that a diver would reference. This speed can be increased or decreased based on how hard the diver throws down his arms in the beginning of the dive as depicted above in figure 2-2. However, a diver can also change his angular velocity by changing his position in the air. To increase speed a diver could pull his legs into his body so as to decrease his radius of gyration and thus decrease his moment of inertia (Batterman, 1968). The momentum of the diver in the air is equal to the moment of inertia multiplied by the angular velocity. Since momentum is conserved, it the moment of inertia increases, the angular velocity must increase. These concepts are commonly used by divers to complete dives that may be difficult or conversely to slow down an easy dive.

2.4 Modeling Methods of Diving

Diving is a very complex sport and because the physics tends to be unique for each athlete there is no one ideal way to simulate diving. Therefore this section is split into subsections that cover a variety of different studies, all of which attempt to simulate diving. Although all of these studies aim to model diving, none of the studies researched the effect of changing techniques such as hurdle length or number of oscillations. The first study uses springs in the model, the second study is highly focused on the controls of diving, and the third method is strongly calculus based using the equation of center of mass and momentum.

2.4.1 Spring Method

A study done in 2006 by Yeadon, investigated methods to model diving. The study represented the diver as an eight-segment body. Each segment was attached to a fixed mass through two parallel and perpendicular undamped springs as shown in figure 2-3.

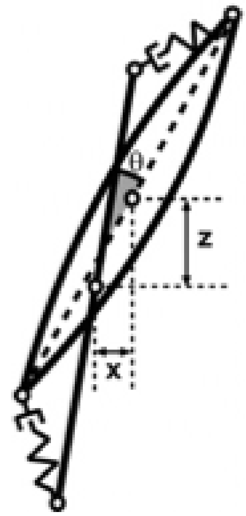

Figure **2-3**: The thigh represented as a solid mass and spring system (Yeadon, 2006)

The spring force was defined as $F=-kx^3-cw$ where k is the stiffness, x is the displacement, c is the damping and v is the velocity. The investigators also simulated the contact with the diving board with springs. However in the foot measurement there were two forces measured, the perpendicular force and the parallel force. The investigators thus used two equations: $F_1=-k_1z-c_1|z|v_1$ and $F_2=|z|(-k_2x-c_2|x|v_2)$ where k is the spring stiffness, c is the damping coefficient, x is the parallel displacement, z is the perpendicular displacement, and v is the velocity. F_1 refers to the parallel force and F_2 refers to the perpendicular force. The investigators input these equations into FORTRAN code in order to simulate the divers. They then used high-speed cameras in order to capture a number of actual dives. Using ten different landmarks on the body, the dives were digitized. The digitized results were compared to the simulated results. The overall outcome of the study was successful in finding that the two methods closely matched as the digitized diver followed the path of the computer model (Yeadon, 2006).

2.4.2 Control Method

A second study by Wayne Wooten and Jessica Hodgins also attempted to capture the motion of a diver using a computer simulation. The investigators modeled the diver as a rigid body with fifteen segments all connected by rotary joints. The joints have either one or more axis depending on the physiological function of the specific joint in the body. The study greatly discusses the idea of controls in diving. In order to perform an action with one part of the body, the diver must control another part of his body. For example, in order for a diver to jump off a tower, his feet must be controlled and in stable contact with the tower. In the air the diver must also control bending at the hips, waist, and knees. Using the control theory the researches created an equation, which represents the torque each joint creates. The equation is $\tau=k_p(\Phi_d-\Phi)+k_v\Phi$ where τ is the torque, Φ is the joint location, Φ_d is where the joint is desired to end up, and k_p and k_v are constants. After the investigators used the above equation to help simulate dives, they compared the simulation to video recordings of Olympic divers. It was found that the model was close to the real divers but not exact, due to the many assumptions that had been made (Wooten, 1995).

2.4.3 Calculus Based

An additional study performed at Princeton attempts to create a simplified model that still does a sufficient job representing a diver. The diver is modeled as four solid links with variable angles at the shoulder, hip, knee, and foot. Assuming the links to be solid rectangles, the investigators derived the center of mass of the diver. They then derived the angular momentum with respect to the center of mass of the diver. The investigators viewed the dive in three separate phases. The first phase was getting into a smaller position to increase rotation, the second phase was the actual rotating, and the third phase was elongating to slow down the rotation. The time getting into position and out of position were assumed to be equal. Using a variety of complex equations and the fact that momentum is conserved so the overall change in momentum is zero; the investigators simplified the problem into smaller more simplified equations. One new equation is in the form of the Euler –Lagrange equation and it is $\int_{t_0}^{t_1} \sum_{i=2}^{4} \ddot{\theta}_i^2 dt$ where θ is the angle between body parts. This equation is minimized to find the trajectory. Also, the times of the first and third phases multiplied by the angle must equal 2kπ. Using the simplified equations and assumptions the investigators were able to simply model the trajectories of divers in a physically realistic way. The model, which is based off simplified equations, creates a starting point for future modeling using fewer assumptions (Lui Z, 1994).

2.5 Summary

In this chapter the basic skills of diving were discussed. The types of diving, directions and techniques were all discussed. This chapter also focused on the biomechanics of diving, which are greatly influenced by the idea of conservation of momentum. Momentum for a diver is generated on the board and cannot be obtained once in the air, although it may be transferred from one part of the body to another. The final subject of this chapter was the modeling of diving. Since diving is such a complex and individualized sport, there are a variety of methods of simulation, but none create a perfect model, so it is still a constant area of study.

Chapter 3

Methods

3.1 Overview

This chapter covers all the methods used to complete this study. The sections included are subjects, testing procedures, data processing, and statistical analysis.

3.2 Subjects

This test used 3 subjects, all members of the Penn State Varsity team. The subjects were all between the ages of 18 and 21 and have been consistently diving for several years. All participants were free of any injuries that would affect the outcomes of this study. Table 3-1 below indicates the heights, masses, genders and ages of all the divers.

Table **3-1**: Heights, masses, genders and ages of subjects

Oscillations	**Height (cm)**	**Mass (kg)**	**Gender**	**Age (years)**
Subject 1	162.56	63.50	Female	21
Subject 2	157.48	56.25	Female	19
Subject 3	170.18	77.11	Male	18

3.3 Subject Testing

There were two separate experiments run in this study. The first tested the height based off the length of the hurdle and the rate or rotation based on the length of the hurdle. The second tested the height based on the number of oscillations in a back press and the rate of rotation based on the number of oscillations in a back press. For all tests the fulcrum was placed at the middle setting of 5 so that the board would have equal spring for each trial.

The first test was performed on the diving board with a forward hurdle. Subjects did one step hurdles consisting of various lengths. These lengths included 12cm, 24cm, and 36cm. From the hurdle, each diver performed a forward dive with one and a half somersaults. The divers were recorded using a Sony Handycam with a frame rate of 25 fps. The video was later processed to find height and rate of rotation.

The second test measured the height and rate of rotation the divers obtained based on the number of oscillations in a back press. This study incorporates the spring-like qualities of the diving board. The subject performed back presses with 0, 5, and 10 oscillations. For this test the subjects completed a back dive with two somersaults following the oscillations. Similarly to the forward tests, the subjects were videotaped using 2D camera technology.

3.4 Data Processing

The data was processed by using the program Kwon 3D. The first step was the calibration of the area. The diving boards and surrounding area were calibrated by marking with black tape, videotaping the area, and inserting the actual distances into the program. The video clips from each trial were then individually loaded into the program. On each frame there was a point placed on the shoulder and the hip. The program found the data points of the trajectory for the path of line connecting the shoulder and hip for each diver. Kwon 3D used this data to find the maximum height of the point on the hip and the rotational velocities of the divers. The maximum heights and average velocities for each trial were recorded. A screen shot of the program can be seen below in figure 3-1. The digitized data was filtered digitally at 10Hz with a low-pass filter with zero-lag. The filter was a 4th-order Butterworth filter. The filtered data was then used for further analysis.

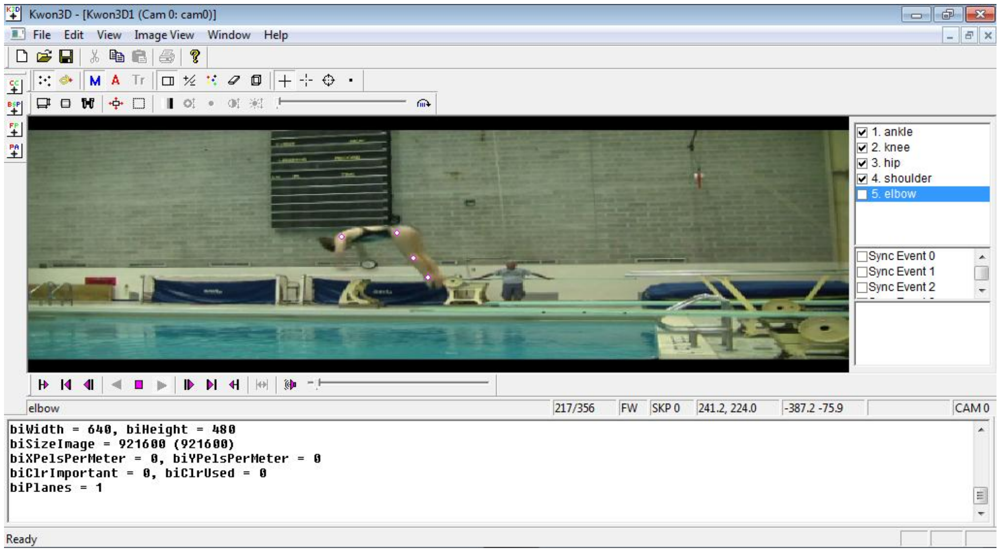

Figure 3-**1**: Screen shot of Kwon 3D

Additional data processing was completed. Using subject 2 and one trial from each of the above tests, an additional model was created. To create this model more points were placed. The points were placed on the ankle, knee, hip, shoulder and elbow. Using the data points the angular momentum of the different body parts was found, giving additional and more accurate information. In order to do this, the data was resampled with 170 frames.

Kwon3D works by taking the digitized points and interposing them with the calibration grid. The calibration grid is made by the user giving the program the actual distance in the screen view. The program can then find the distances the digitized points have traveled in the form of the x and y locations on the grid. The highest y point for the data of each subject was considered the maximum height. The program was also able to calculate the angular velocity. The velocity is calculated by dividing the distance the points traveled by the time it took to travel. A final use of the program was to find angular momentum. Angular momentum is the moment of inertia multiplied by the angular velocity. For this calculation the moment of inertia was taken an estimated equation using the subject's height and weight.

3.5 Statistical Processing

Repeated measured ANOVAs were used to explore how the average height and the rate of rotation were affected by factors of hurdle lengths (3 levels: 12cm, 24cm, and 36cm) and the number of oscillations (3 levels: 0, 5, 10). Also, Tukey's honestly significant difference and pairwise contrasts were used to explore significant effects. In order to do this test the data was normalized using the maximum jump heights of the subjects. This maximum height was found by the subjects jumping on solid ground and measuring the height jumped. The maximum jump heights were 45cm for subject 1, 43 cm for subject 2, and 73.66 cm for subject 3. Since one subject was male and the other two were female, all with different jumping abilities this helped to decrease the standard of deviation between the subjects. The final results shown in chapter 4 are not normalized so the trend of the raw data of each individual subject could be seen. The data was normalized for statistical processing, because when taking the standard deviation between subjects with large variances in jumping abilities without normalization, the statistical processing would not reflect the true differences between the different variables. The factors were hurdle length and number of oscillations and alpha was set to .05. The values indicated that the differences based on the factors indicating that the middle number of hurdle length or oscillations were not statistically significant. However, the larger number and middle number of oscillations were significantly higher than the smallest number of oscillations for height as P=.01. This was followed up by post hoc testing showing that the two larger numbers of oscillations were significantly higher than no oscillations.

Chapter 4

Results

4.1 Introduction

This chapter presents the results from the study. The first section holds the results subject height based on hurdle length. The second section contains the results for subject rate of rotation based on hurdle length. In the third section are the results from subject height based on number of oscillations. The final section contains subject rate of rotation based on rate of rotation.

4.2 Height Based on Forward Hurdle

The heights achieved by each subject are listed in table 4-1. The heights listed are the average height of all the trials per each hurdle length. The data is also presented as a graph in figure 4-1. Figure 4-1 shows all the data points for each subject as well as a line depicting the average of all the subjects. Figure 4-2 shows the data normalized.

Table **4-1**: Average achieved heights per hurdle length

Hurdle Length	**12cm**	**24cm**	**36cm**
Subject 1 (cm)	161.09±25.97	182.54±4.09	171.00±6.33
Subject 2 (cm)	175.34±1.95	180.89±1.96	177.97±5.42
Subject 3 (cm)	246.90±8.46	253.86±9.98	228.93±2.91
Average	194.44	205.76	192.63

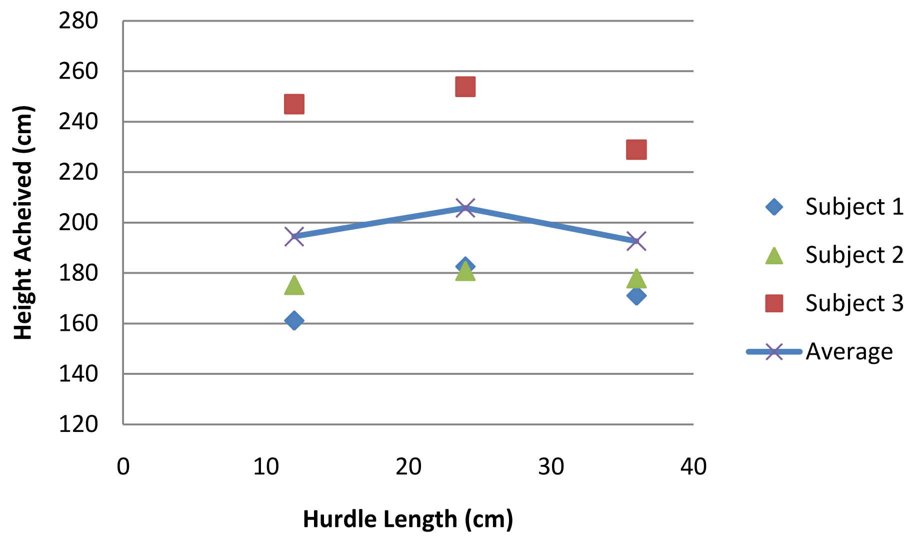

Figure **4-1**: Average subject heights achieved vs. hurdle length

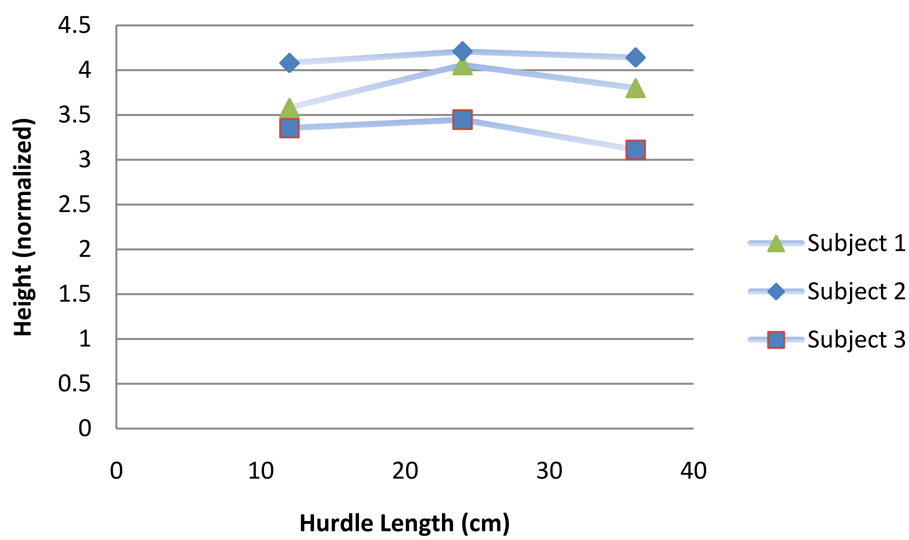

Figure **4-2**: Normalized subject heights achieved vs. hurdle length

4.3 Rate of Rotation Based on Forward Hurdle

The rates of rotation of each subject are listed in table 4-2. The data is the average rate of rotation of all trials for each subject per each hurdle length. Figure 4-3 shows the data points of the rate of rotation for all subjects versus the hurdle length. It also shows a line for the average of all the subjects. The rate of rotation is measured in radians per second. Figure 4-4 shows the normalized data for each subject.

Table **4-2**: Average rate of rotation achieved per hurdle length

Hurdle Length	**12cm**	**24cm**	**36cm**
Subject 1 (rad/s)	8.89±.42	8.47±.10	7.79±.35
Subject 2 (rad/s)	8.90±.47	9.88±.62	8.80±.23
Subject 3 (rad/s)	8.36±.65	9.71±.94	8.93±.78
Average	8.72	9.35	8.51

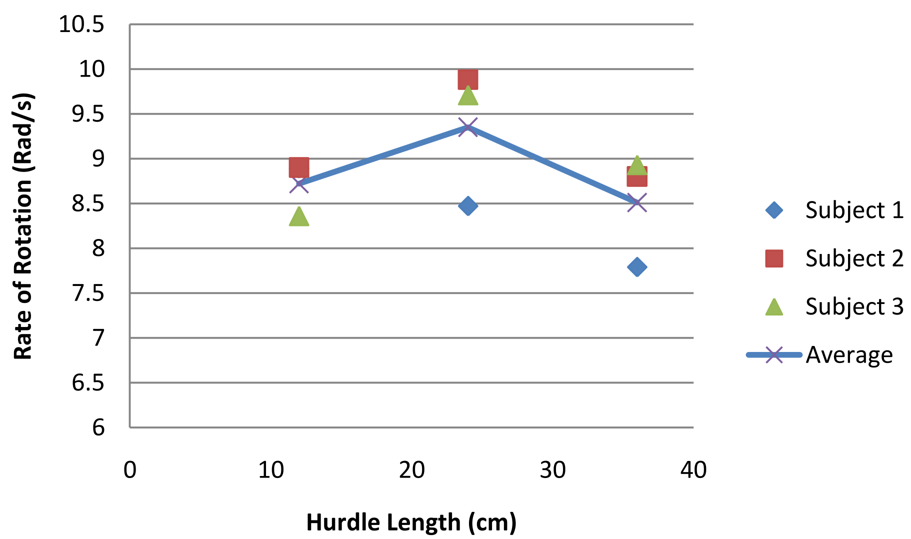

Figure **4-3**: Average subject rate of rotation vs. hurdle length

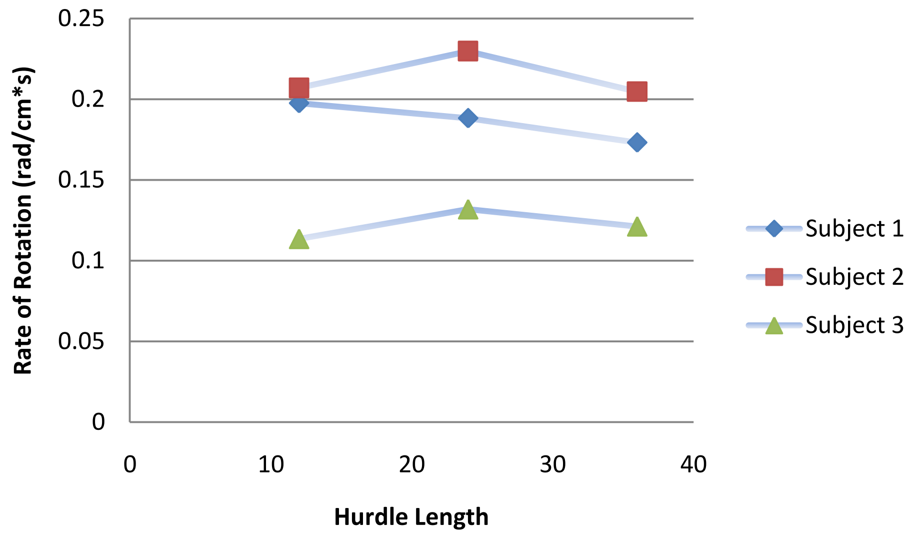

Figure **4-4**: Normalized subject rate of rotation vs. hurdle length

4.4 Height Based on Backward Oscillations

The heights achieved by each subject are listed in table 4-3. The heights listed are the average height per each number of oscillations for all trials. The data is also presented as a graph in figure 4-5. The values in figure 4-5 are the individual average data points and a line for the average of the averages for each subject. The normalized data for each subject is also shown in figure 4-6.

Table **4-3**: Average achieved heights per number of oscillations

Oscillations	**0**	**5**	**10**
Subject 1 (cm)	149.97±3.33	159.32±4.87	161.62±2.50
Subject 2 (cm)	143.48±5.05	172.75±4.36	165.07±6.03
Subject 3 cm)	167.03±6.47	223.65±7.13	214.09±1.19
Average	153.49	185.23	180.25

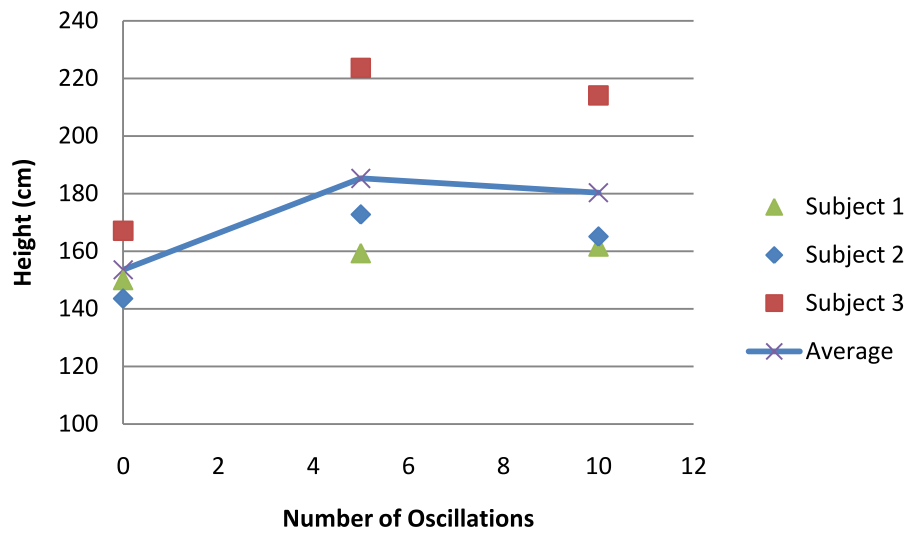

Figure 4-5: Average subject heights achieved vs. number of oscillations

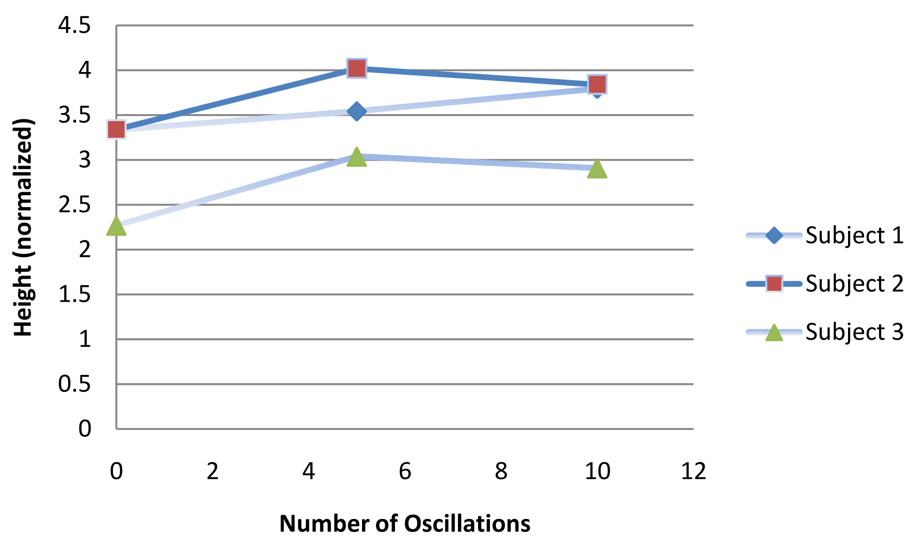

Figure 4-6: Normalized subject heights achieved vs. number of oscillations

4.5 Rate of Rotation Based on Number of Oscillations

The average rates of rotation from each subject are listed in table 4-4. The data is also presented as a graph in figure 4-7. The line in figure 4-7 is the average of the averages for each subject. There are also individual data points depicting each subject's averages. Figure 4-8 presents the normalized data for each subject.

Table **4-4**: Average rate of rotation per number of oscillations

Oscillations	**0**	**5**	**10**
Subject 1 (rad/s)	12.41±.13	12.11±.21	11.87±.13
Subject 2 (rad/s)	11.46±.60	11.87±1.04	10.67±1.00
Subject 3 (rad/s)	12.37±.13	12.84±.32	12.71±.57
Average	12.08	12.27	11.75

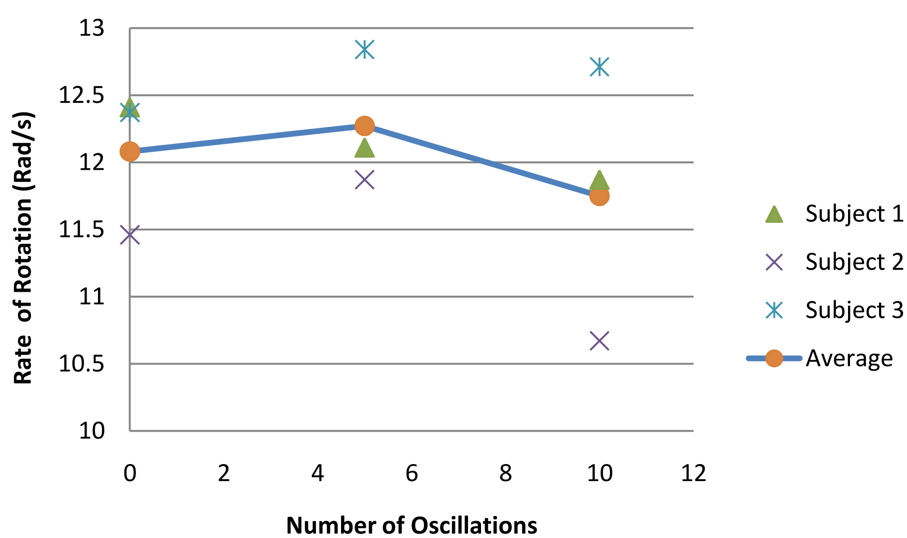

Figure 4-7: Average subject rate of rotation vs. number of oscillations

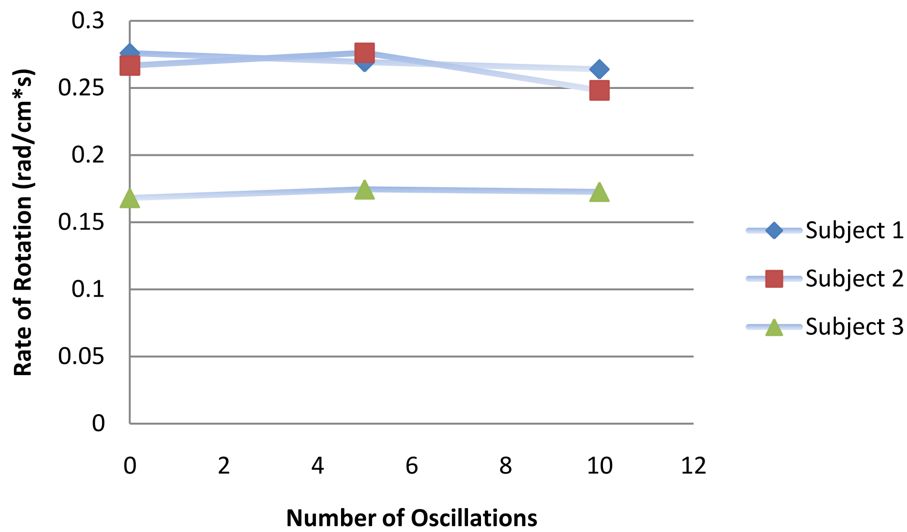

Figure 4-8: Normalized subject rate of rotation vs. number of oscillations

4.6 Momentum from Forward Hurdle and Back Press

Momentum was found for different body parts during both the forward hurdle and the backward takeoff. The whole body momentum was also found to be relatively constant throughout the dive. For simplicity, only subject 2 was used for this modeling. Subject 2 was chosen because this subject overall had the lowest standard of deviations between the trials for each test. The momentum throughout the dives of the shank and the thigh are depicted in figures 4-5 through 4-8. The vertical axis is the momentum in kg*m/s and the horizontal axis is the number of frames. The data has been resampled to 170 frames. In forward hurdles shank and thigh 1 refer to a hurdle length of 12cm, shank and thigh 2 refer to a hurdle length of 24cm, and shank and thigh 3 refer to a hurdle length of 36cm. Similarly for back presses, shank and thigh 1 refer to 0 oscillations, shank and thigh 2 refer to 5 oscillations, and shank and thigh 3 refer to 10 oscillations. The takeoff point is around 10 frames, which is where all the lines meet with a momentum around 0. The graphs are shown below in figures 4-5 through 4-8.

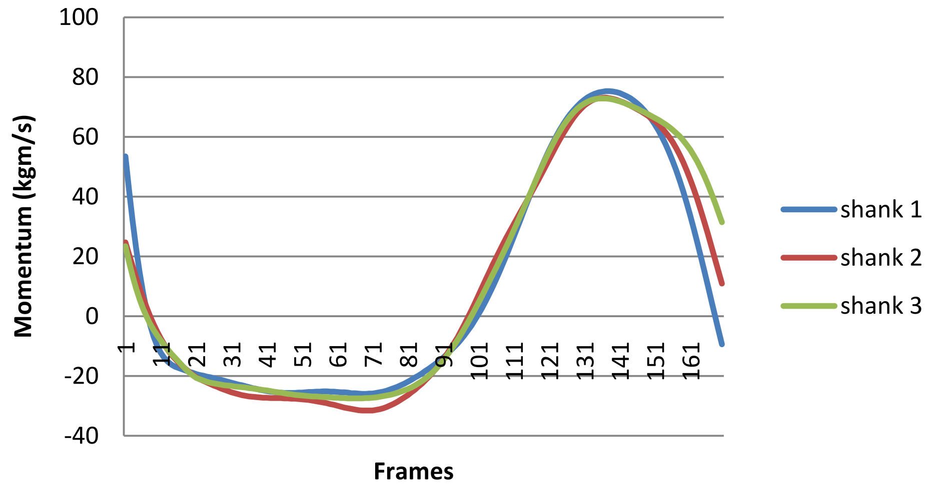

Figure **4-9**: Momentum of shank in forward hurdle

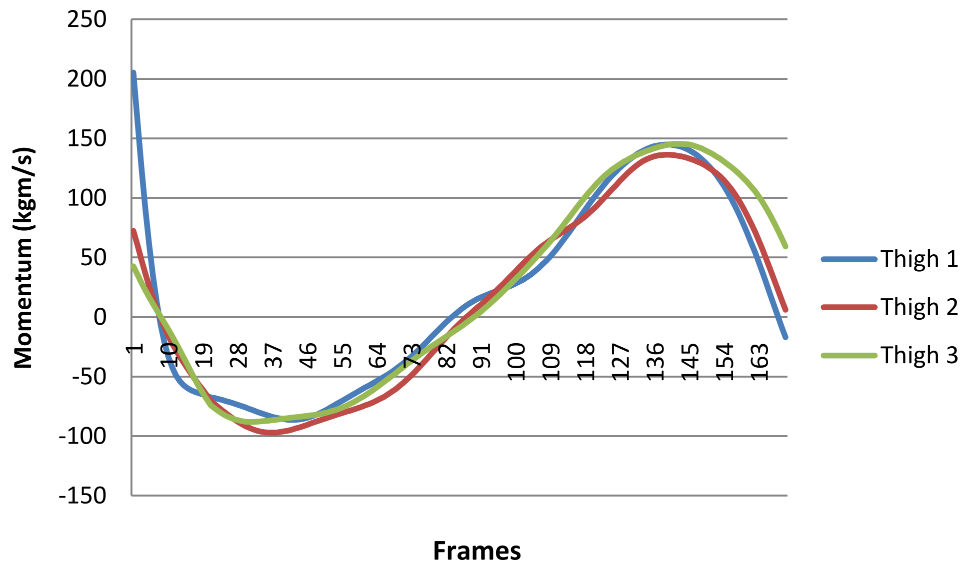

Figure **4-10**: Momentum of thigh in forward hurdle

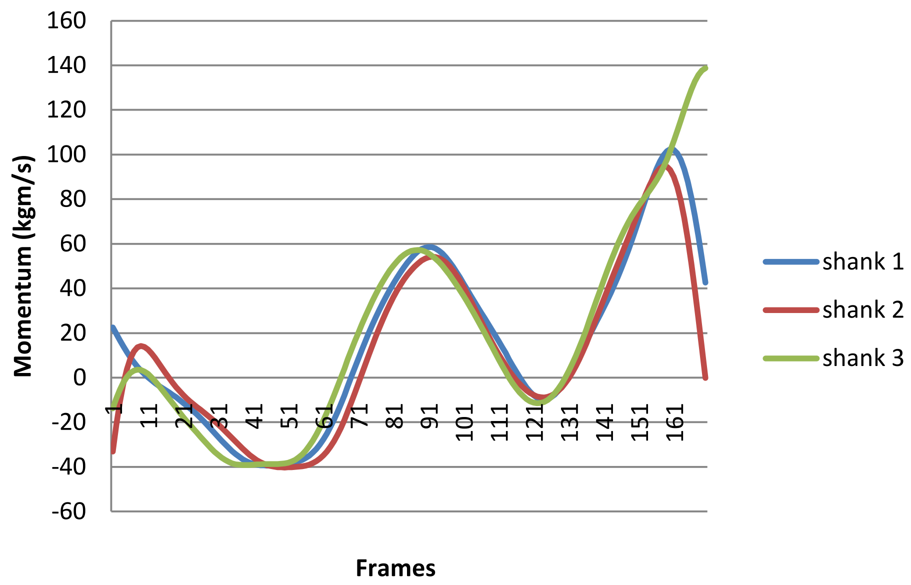

Figure **4-11**: Momentum of shank in back press

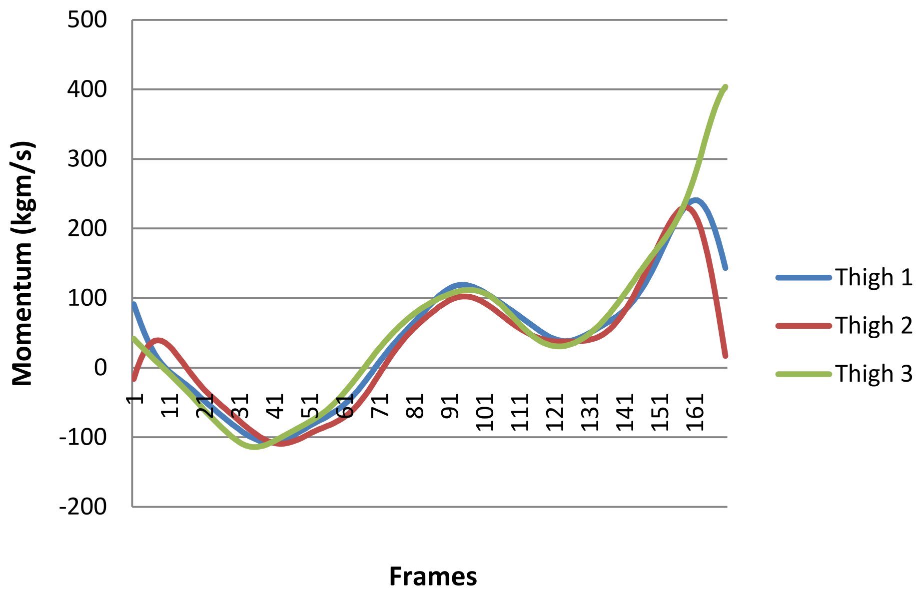

Figure **4-12**: Momentum of thigh in back press

Chapter 5

Discussion

5.1 Overview

This final chapter discusses the study. First, the results and the implications of the results will be presented. Next, the limitations of this study will be discussed. In the following section, areas for future study will be acknowledged. Finally, the chapter will end with conclusions of the study.

5.2 Discussions of Results

This section will be divided into four subsections. The first section will address the results from varying the length of forward hurdle. The second section will discuss the results of varying the number of oscillations during a backwards press. The third section will discuss the results from the additional data processing of both the forward hurdle and the backward press. The final section will relate what the results would implicate to an actual diver.

5.2.1 Varying the Forward Hurdle

The subjects performed hurdles at three different hurdle lengths in order to find if any one length was superior. Superior would be defined as aiding the diver to gain more height and angular velocity during the dive. Qualitatively, the middle hurdle length of 24cm was the optimal length. On average, it did allow the divers to gain the greatest amount of height and speed during rotation. During the trials this hurdle length also appeared to be the most comfortable stride length for the subjects as they kept the best upright posture. These results therefore indicate that a diver will gain the most benefit from a hurdle that has a length that is an average and comfortable length.

5.2.2 Varying the Backward Press

The results of the backward press were very similar to that of the forward hurdle. The subjects performed back presses with one of three different numbers of oscillations. The goal was to find the number of oscillations that provided the diver with the most momentum to gain the most height and the fastest rotation speed. Like the forward hurdle, qualitatively the middle number of oscillations allowed the divers to gain the most height and spin the fastest. At this middle number of oscillations, the subjects had gained momentum, but had not lost balance, which would be indicated by the diver falling backwards. Finding a good, but small number of oscillations can allow a diver to perform a dive better by allowing for more air time due to a higher jump and a faster rotation speed.

5.2.3 Additional Data Processing

The results of the data processing did not show a clear superior technique in terms of momentum. All of the trials gave a very similar depiction of the change in momentum over time. This is as expected, as the subject is a very qualified diver and will almost innately perform actions necessary to gain the desired momentum. For the backward take-offs the momentum does seem to be a small amount higher for the largest amount of oscillations. This also makes sense because the longer the diver oscillates the board the more momentum is gained. However, just because the diver has more momentum, does not mean that he gains more height. If the increased momentum causes the diver to lose balance and have a more horizontal trajectory then the dive will be harder to complete because the air time will be shortened.

A similar study was done by Hamill in 1986 measuring the momentum of a diver through the air coming off a platform. The study found the momentum of the whole body at take-off to be -50.89 kg*m/s for the forward one and a half somersaults (Hamill, 1986). However, the data processing for the present study showed the momentum for the whole body to be -240.77 kg*m/s. This discrepancy is most likely because a diver taking off from a spring board would gain much more momentum than a diver taking off from a rigid piece of concrete. Therefore, the fivefold difference between the published results and the calculated results is as expected.

Overall this model shows that the momentum difference between the trials is minimal and should not be a deciding factor in deciding hurdle length or number of oscillations.

5.2.4 Implications to a Diver

The differences in the distances may not seem overly large. However, even a small distance may make an impact on a diver. For an example data from subject 3 was used. For the height from the forward hurdle the subject reached 253.86cm for a 24cm hurdle and 228.93cm for the 36cm hurdle. This is a difference in height of 24.93cm. This means that the diver would actually have 49.86cm more in the air after the 24cm hurdle, when considering going both up and down. The time it takes just for the downward portion can be estimated using $\Delta x = v_o t + \frac{1}{2}at^2$, where x is the distance traveled, v_o is the initial velocity, t is the time, and a is acceleration. For this problem x=24.93cm, v_o=0 since the topmost peak of the trajectory is being considered, a=-9.81m/s^2, and the variable being solved for is t. Using this equation t=.23s and this is only the extra time gained on the way down. Additional time will be gained on the way up. Nonetheless, .23s is enough time to grab one’s hands or to even turn one’s palms toward the water. Both of these actions allow the diver to enter the water with less splash and thus perform a better dive.

5.3 Limitations of the Present Study

There were numerous limitations on this study. The camera used to film the divers was a simple low speed household video camera. A high-speed camera would have allowed for crisper images and thus an increased ability to define body parts during data processing. Also, since the subjects were entering into water, reflective markers could not be added to their bodies. Therefore, the software could not automatically pick up the joints of interest and they had to be entered manually. This manual clicking was a major source of error in the study.

Modeling the actions of the diver was another limitation of the study. Diving is a very complex motion, as the diver's body shape does not stay constant as it is flipping through the air. Using a program such as Matlab to create a model could have created a useful model to simulate the diving, but would have taken an abundance of time. Therefore, due to a lack of time an advanced model was not created.

A final and very significant limitation was the small sample size. This study only used three subjects. In order for statistical significance there would need to be a very large amount of subjects. However, in order to keep the standard deviation low between the trials of each subject, the subject must be well qualified. This was defined as being a competitive diver on the collegiate level. During the time the study was performed there were only three Penn State Varsity divers available to participate. Qualitatively there was a difference between the variables, but quantitatively the differences were small. More subjects would have added more data and made the small differences more significant.

5.4 Future Studies

Future studies should address the concerns addressed above in the limitations. A higher speed camera should be used; as well as some waterproof marking system should be devised. Adding a sophisticated model would help to add both data and credibility. Future studies should also include many more subjects.

This study only addressed height, rate of rotation, and momentum. A future study could be more comprehensive and include more variables. For each experiment there was also only three different lengths of the hurdle and number of oscillations. Adding more trials could spread out the curve showing more defined results.

This study was also only done in a 2D frame. However, diving is done in a 3D frame. Using special software to capture and analyze the 3D image would allow for more realistic results. Using 3D would also allow twisting dives to be analyzed, in which most of the arm movements are within the unused dimension of depth.

5.5 Conclusions

The study demonstrated that by changing hurdle length or number of oscillations a qualitative difference can be observed for height and rate of rotation. However, a change in momentum is too miniscule to be observed between the different conditions. Using the average number for both variables allowed the subject to gain more height and spin faster. If the diver has more height on the way up, he also has that extra distance on the way down. Also, if the diver spins faster, he can complete flips sooner before reaching the water. Thus the average hurdle length and number of oscillations will allow a diver to complete a dive high above the water allowing for more time to prepare for a perfect entry. However, further studies will be necessary to find quantitative results that are statistically significant before coming to a definite conclusion.

REFERENCES

(1968). In C. Batterman, *The Techniques of Springboard Diving* (pp. 1-4). Boston: The Massachusetts Institute of Technolody.

Duraflex. (2003-2008). *Duraflex Diving Boards*. Retrieved Aug 4, 2010, from Duraflex International: http://www.duraflexinternation.com/index.php

Frohlich, C. (1978). Do Springboard Divers Violate Angular Momentum Conservation. *American Journal of Physics*, 47: 583-592.

Hamill, J. R. (1986). Angular Momentum in Multiple Rotation Nontwisting Platform Dives. *International Journal of Sport Biomechanics*, Vol 2, 78-87.

Lui Z, C. M. (1994). Decomposition of Linked Fingure Motion: Diving. *5th Eurographics Workshop on Animation and Simulation*.

O'Brien, R. (2003). *Springboard and Platform Diving.* Champaign: Human Kinetics.

Rubin, B. (1999). The Basics of Competitive Diving and Its Injuries. *Clinics in Sports Medicine*, 18:2:293-303.

Wooten, W. H. (1995). Simulation of Human Diving. *Computer Graphics Forum*, 12(1):1-11.

Yeadon, M. K. (2006). Parameter Determination for a Computer Simulation Model of a Diver and Springboard. *Journal of Applied Biomechanics*, 22:167-176.

Zatsiorsky, V. (2000). Biomechanics in Sport: Performance enhancement. In *Encyclopaedia of Sports Medicine.* London, UK: Blackwell Science Ltd.

Appendix A

Academic Vita of

Ilana Zeises

Name

Ilana Zeises

Email ID

IJZ5000@psu.edu

Education

Bachelor of Science in Bioengineering

Pennsylvania State University, University Park, PA 16802

Anticipated Graduation: Spring 2011

Honors: Kinesiology and Bioengineering

Thesis Title

"The Effect of Hurdle Length and Frequency of Oscillations on Height and Rate of Rotation in Diving"

Thesis Supervisor

Dr. Zatsiorsky, Ph.D.

Experience

Note taker **August 2010-January 2010**

Pennsylvania State University University Park, Pa

Bioe406

- Typed Notes
- Submitted to Office of Disabilities

Lab Assistant **January 2008-May 2008**

Pennsylvania State University University Park, Pa

EDGSN 100

- Helped students with Solidworks
- Taught material
- Create and graded exams

Diving Coach **July 2008; 2009; 2010**

Pennsylvania State University University Park, Pa

Penn State Diving Camps

- Coached a group of divers
- Took care of divers overnight

Service

Hospital Volunteer **June 2009- Present**

Mount Nittany Hospital State College, Pa

- Transported Patients
- Exchanged dirty and sterile equipment
- Transferred lab specimens and reports
- Kept Emergency Room linens stocked
- Made beds

Swim Coach **January 2008-Present**

Special Olympics Centre County State College, Pa

- Helped to prepare Special Olympic athletes for swim meets
- Traveled with athletes to meets
- Set up and broke down work for the State games

Honors/ Awards

Schreyer Honors College, Fall 2009-Spring 2011

Alpha Eta Mu Beta Honors Society, founding member Spring 2010

Phi Kappa Phi Honors Society, inducted Fall 2009

Omicron Delta Kappa Honors Society, inducted Fall 2009