DIFFERENCES IN GROUND REACTION FORCES BETWEEN TAKE-OFFS THAT ARE OUT, ON, OR UNDER IN THE POLE VAULT

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ABSTRACT

Aim. The take-off is regarded as the most important phase of the pole vault yet there is an insufficient amount of research on the ground reaction forces of the pole vault take-off. At this time there is not any scientific research comparing force and time between take-offs that are out, on and under. The purpose of this study is to compare the differences in ground reaction forces between pole vault take-offs that are out, on or under.

Methods. Over five days, 15 male and female college pole vaulters completed 226 vaults on a (AMTI Accupower) force plate. The jumps were put into categories of out, on and under and analyzed by Accupower, and Dartfish software. Separate mixed modal ANOVAs (SAS 9.3) were applied ($P \leq .05$) for comparison between jump types.

Conclusions. There is no significant difference between ground reaction forces of the three jump types.

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DEDICATION

I would like to dedicate this thesis to my amazing parents, Dennis and Mary Francis. They have always taught me that life is too short to be anything but happy. If you aren't doing what you love than you need to make a change. I would also like to dedicate this to every pole vaulter out there. There really isn't anything like the pole vault community.

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CHAPTER 1. INTRODUCTION

USA Today selected pole vaulting as the third-hardest thing to do out of all sports (Mihoces, 2003). What makes the sport difficult are the different variables of the event that include, but are not limited to, the speed of the athlete, size, skill level, pole choice, grip on the pole, standard setting, and different techniques. Most experts agree that superior pole vaulters are unique athletes. An elite pole vaulter is said to have the speed of a sprinter, the acrobatics of a gymnast, the strength of a power lifter, and has the risk-taking attitude of an extreme sports athlete. With so many variables and athletic uniqueness, experts agree that the take-off is the most important phase of the pole vault (Plessa, Rousanoglou, & Boudolos, 2010).

Professionals in athletic performance and track and field use science to determine the best ways to enhance athletic performance. Improvements in technology allow researchers to advance the quality and speed of their research. Biomechanical analysis using digital video and software data have improved the overall understanding of movement. Force plate analysis has progressed researchers' understanding of kinematic and kinetic factors in sports. Having a better understanding of pole vault variables through biomechanics, kinematic factors, and kinetic factors, has enhanced pole vault performance (Launder & Gormley, 2008).

Statement of the Problem

Previous research focused on methods to minimize energy loss during the pole vault to increase maximum height (Barlow, 1973; Gros, 1982). The take-off is regarded as the most important phase in the pole vault. There is an extensive amount of research on pole vault velocity and take-off angles, and their effect on maximum vertical height. However, there is a scarcity of information regarding ground reaction force. There are only two articles to my knowledge by Barlow (1973) and Plessa et al. (2010) that measure ground reaction force and ground contact time of the take-off leg in the pole vault.

Numerous pole vault techniques emerged since the late 1940s when fiberglass poles were introduced. Vital Petrov and his creation of the Petrov/Bubka pole vault model produced the world record for both men and women in the pole vault. In his book, *From Beginner to Bubka*, Alan Launder discussed the Petrov model in detail. A popular aspect of the Petrov model is the free take-off. A free take-off happens when the vaulter takes off while the pole remains unloaded (Launder & Gormley, 2008). The take-off foot is just behind the top hand at the moment that the foot leaves the ground. There is some confusion with the terminology because the terms a free take-off, pre jump, and out take-off have been used interchangeably. For the purpose of this discussion, the term out take-off will be used. The model suggests that by taking off slightly further away from the vault box rather than directly under the top hand, less energy will be lost and the vaulter will be taller during the take-off. As of yet, no published research has measured the difference in ground reaction force of the take-off when the vaulter takes off on, under, or out in the pole vault.

Purpose

The purpose of this study is to compare the differences in ground reaction forces between pole vault take-offs that are out, on or under.

Specific Objectives

- To compare vertical ground reaction force for pole vault take-offs that are on, under and out
- To compare breaking ground reaction force for pole vault take-offs that are on, under, and out
- To compare propulsive ground reaction force for pole vault take-offs that are on, under, and out
- To compare medial ground reaction force for pole vault take-offs that are on, under, and out
- To compare lateral ground reaction force for pole vault take-offs that are on, under, and out
- To compare total time on the force plate for pole vault take-offs that are on, under, and out
- To compare propulsive time on the force plate for pole vault take-offs that are on, under, and out
- To compare breaking time on the force plate for pole vault take-offs that are on, under, and out

Limitations

1. The investigator will be unable to control the environmental factors of each subject which may have affected individual performances. These factors may include sleep, training cycle, nutrition, and physical condition.

2. The subjects may be jumping differently due to their knowledge of being tested.

3. Motivational aspect of competition may be diminished.

4. The sample size is limited to only North Dakota State University pole vaulters.

Definition of Terms

Approach Run - The phase of the vault preceding take-off during which the vaulter, from a starting position, attempts to steadily increase his or her forward horizontal velocity and momentum up to the point at which he or she leaves the ground (Barlow, 1973).

Breaking Force- The component of force generated in a direction opposite to the approach run by contact with the take-off foot (Barlow, 1973).

Center of Gravity – The point of the body through which the resultant of the earth's pull upon the body passes and at which the total weight of the body can be considered acting (Barlow, 1973).

Dartfish – Video analysis software used to study biomechanical factors in sport.

Force Plate – A measuring instrument used in athletic, clinical, and research setting that measures ground reaction forces generated by a body. The device is used to measure many parameters of biomechanics, such as gait and balance.

Free Take-off – (Also known as a “Pre-Jump”) Occurs when the vaulter takes off the ground and the pole is still unloaded or ridged. The take-off foot would be directly under the top hand, but the pole tip would only touch the back of the box the instant the foot leaves the ground. The take-off foot is just slightly behind the on take-off. A free take-off also falls into the category of an out take-off.

Ground Contact Time – The time in which the foot makes contact with the ground until the moment it leaves the ground.

Ground Reaction Force – The reaction to the force that the body exerts on the ground.

On Take-off - When the take-off foot is directly under the top hand at take-off. The tip of the pole touches the back of the plant box at the same time that the foot extends off of the track.

Out Take-off- When the take-off foot is behind the top hand at take-off. Similar to the free take-off, but the out take-off foot can have a greater distance from an on take-off than a free take-off .

Plant – The phase of the vault which is initiated as the pole tip starts to advance and drop relative to the vaulter’s body and finishes when the top hand is extended vertically at the highest point.

Stride – The sequence of the approach run which occurs from the moment one foot breaks contact with the running surface to the point at which the opposite foot of the recovery leg touches the running surface and also breaks contact (Barlow, 1973).

Take-off – The moment the take-off foot touches the ground during the plant to the moment the vaulter leaves the ground.

Thrusting Force – The component of force generated in the same direction as the approach run by contact with the take-off foot (Barlow, 1973).

Under Take-off - When the take-off foot is closer to the vault box than the top hand. The pole tip strikes the back of the box before the vaulter leaves the ground.

CHAPTER 2. LITERATURE REVIEW

The purpose of this study is to compare the differences in ground reaction forces between pole vault take-offs that are out, on or under. The literature review will examine specific articles that pertain to pole vault and, more specifically, the pole vault take-off. In this chapter, the literature is arranged in the following order: pole vault origins and equipment, physics of the pole vault, and similarities between the long jump and the pole vault take-off.

Pole Vault Origins and Equipment

The origins of the pole vault are uncertain. Warmerdam (1947) suggested that pole vaulting started in northern England due to the large amount of small streams and dykes. Early competitions used poles to jump for height and distance. In 1873, the Princeton Caledonian Club instituted the event, which became part of the intercollegiate track and field program in the United States (Ganslen, 1971). Early competitive pole vault poles were made of hickory wood, which could have weighed more than 30 pounds (Dillman, & Nelson, 1968). Changes in pole vaulting equipment were made to improve performance and safety. Lighter bamboo poles replaced wooden poles in an effort to maximize speed on the runway. Holes were dug into the ground which would later lead to the pole vault box. As pole vaulters jumped higher, the need for safety intensified. Grass landing areas were replaced by foam, sawdust, and sand (Frank, 1971).

Poles

During the early 1900s, the most successful pole vaulters used bamboo poles. The improvement of technique and scientific analysis and methods of training, rather than equipment, were the reason for increased performance (Coniam, 1963). Warmerdam is known as the greatest pole vaulter of the straight pole era. In 1943, on a bamboo pole, Warmerdam pole vaulted 4.77m to set the world record that he held until the late 1950s. Following World War II, pole vaulters transitioned from bamboo poles to metal poles because of their reliability and light weight (Cooper, Lavery, & Perrin, 1970).

Don Bragg has the best known vault on a metal pole at 4.80m. In the late 1940s and early 1950s, the fiberglass pole was developed. The first fiberglass poles used were unreliable and broke easily. Fiberglass poles eventually became superior due to scientific advances in the development of material (Cramer, 1968). In 1962, the first 4.89m jump was accomplished by John Uelses of the United States. By 1972, the first 5.51m pole vault was completed by Kjell Isaksson of Sweden. In 1981, the first 5.80 m vault was completed by Thierry Vigneron of France. Due to the fiberglass pole technology, the pole vault world record improved over three feet (.9144m) in twenty years and vaulters were jumping higher than they had ever imagined possible (IAAF, 2009)

Bubka

In 1984, Sergey Bubka of Russia advanced the previous world record of 5.83 meters to 5.85 meters. It is without question that Bubka was the most dominating force in pole vault history. Between 1984 and 1994, he broke the world record 35 times, both indoors and outdoors. He was the world champion for 16 years, winning six consecutive gold medals at the world championships. Bubka is the only man to ever clear 20 feet in the pole vault and holds the indoor world record at 6.15 meters and the outdoor world record at 6.14 meters (Launder & Gormley, 2008).

Pole Vault: Women

Pole vault records for women started being officially recorded by the IAAF in 1992 with Sun Caiyun of Nanjing jumping 4.05 meters (IAAF, 2009). The pole vault world record progressed quickly, improving roughly a foot every four years until 2004. The first Olympic pole vault competition for women was held in the 2000 Sydney Olympics, during which Stacy Dragela of the United States jumped 4.60 meters to win the competition. From 1992 to 2003, the world record improved from 4.05 meters to 4.82 meters, held by Yelena Isinbayeva from Russia.

Isinbayeva

What Surgay Bubka did for the pole vault for the men, Yelena Isinbayeva was doing for the women. Isinbayeva holds the indoor world record at 5.00 meters and the outdoor world record at 5.06 meters. She set 27 world records and won nine straight championships between 2004 and 2008 (Launder & Gormley, 2008). Isinbayeva was a two-time Olympic gold medalist and the only woman to have jumped 5.00 meters as of 2011.

Technical and Scientific View of the Pole Vault

The pole vault is considered the most technical event in track and field. Elite pole vaulters start sprinting towards the vaulting box at an average distance of 16 to 22 strides away. They reach speeds up to 9.9 meters per second while carrying a 5.20 meter pole, weighing seven pounds. The vaulter plants the pole into the vault box, the pole bends and propels the athlete vertically over a cross bar. The goal is to jump as high as possible vertically over a cross bar. To achieve maximal results, the vaulter attempts to minimize energy loss through the different phases of the pole vault.

The science of pole vault can be described using physics, kinematics, and kinetics. The pole vault involves the transfer of kinetic energy into gravitational potential energy or vertical height (Pelletier, 2011). Kinetic energy is defined as “Energy due to the motion of an object" (McGinnis, 2005, p. 392). Elastic potential energy, or strain energy, is defined as “Energy due to the deformation of an object; for stretching or compromising" (McGinnis, 2005, p. 395). Gravitational potential energy is energy of a body or system due to gravitational force. A full pole vault involves all three energy transfers. The pole vaulter builds up kinetic energy by sprinting down the runway. As the pole vaulter plants the pole in the box, the kinetic energy is transferred to the pole, creating elastic potential energy. The fiber glass pole bends while lifting the vaulter vertically into the air, transferring the kinetic energy to gravitational potential energy, or maximum force against gravity (Pelletier, 2011).

Technical

There are six basic phases of the pole vault. These phases include the run, the plant, the take-off, the swing, the inversion, and the fly away. Each phase needs to work together to create a pole vault. The continuous chain model suggests that each phase of the pole vault builds upon the other phases. If a vaulter builds up a great amount of speed or kinetic energy during the run up phase, but the take-off was poor, energy will be lost during the take-off. The energy loss cannot be recovered during future phases (Young, 2002).

The Run

The first phase of the pole vault is the run. The pole vaulter chooses a spot on the runway to start, picks up the pole, and starts running. The approach run progresses in speed in order to achieve maximal speed at the take-off. The faster the pole vaulter runs the greater the amount of kinetic energy that will be used for the pole vault. Speed of a pole vaulter is the most important determinate in maximal bar clearance (Barlow, 1973; McGinnis, 2007; Gros, 1982; Launder & Gormley, 2008). “Not all fast vaulters are elite vaulters, but all elite vaulters are fast” (McGinnis, 1989, p. 3472).

Proper sprinting technique is important for maximizing runway speed and setting the vaulter up for an effective take-off. Running with a pole changes the sprinting biomechanics of a vaulter. Due to the added weight of the pole, the center of mass of the vaulter moves forward during the run and the foot strike is slightly ahead of the center of mass compared to a sprinter (Launder & Gormley, 2008). Keeping the pole tip at a high angle reduces the weight and torque placed on the vaulter. During the run, the pole tip gradually lowers, increasing the last three steps of the vaulter and putting them in an ideal position for the next phase (Chang, 2009).

The Plant

The plant is the phase following the run. Six to eight strides away from the box; the pole vaulter lowers the pole horizontally with the runway and initiates the plant. The plant is completed when the back hand is fully extended above the head. Barlow's (1973) study shows that an early plant is ideal in setting the vaulter up for the next phase of the pole vault. Grip on the pole plays an important role in the pole vault. A narrow grip improves the ground take-off angle, but makes it more difficult to plant the pole due to torque forces (Launder & Gormley, 2008). Vitali Petrov noted that the run up and pole plant should be seen as a single integral movement (Launder & Gormley, 2008).

The Take-off

The take-off is often discussed as the most important phase of the pole vault (McGinnis, 1987). The take-off is the moment that the take-off foot touches the ground until the moment it leaves the ground. At take-off, elite pole vaulters have a higher center of gravity, faster horizontal speeds, and faster vertical speeds than lower level pole vaulters at take-off (McGinnis, 2007). McGinnis (1987) found that an optimal take-off angle for elite male vaulters is 15-20 degrees. Barlow's (1973) study found a mean take-off angle of 21.9 degrees. Not all of the subjects in Barlow's study were elite pole vaulters compared to McGinnis' study (2007). Barlow (1973) also found that as bar height increased, the take-off angle also increased. Ground reaction force and contact time will be discussed in greater detail in later sections.

The Swing

An effective plant produces a stretch reflex, allowing the trail leg to whip aggressively forward. The swing can put more energy into the pole vault system. It is of equal importance for putting the vaulter in the proper position for using the elastic energy in the pole. During this phase, elite pole vaulters are able to reduce the length of the pole by thirty percent by bending the pole. Putting more energy in the pole is done by creating torque on the pole by keeping the top arm and take-off leg straight through the swing (McGinnis, 1987). According to McGinnis (2007), changes in technique can change based on the attributes of the vaulter. A shorter vaulter, due to his shorter radius, may swing up to vertical too quickly, causing him to stall. Pressing with the bottom hand will slow down the rotation of the swing, but may make the vaulter late for the next phase of the vault, the inversion.

The Inversion

The inversion phase of the pole vault is when the vaulter is completely upside down on the pole. Sergey Bubka stated that his goal was to be completely inverted when the pole was at its maximum bend (Launder & Gormley, 2008). This allowed him to exploit all of the elastic energy he put into the pole. During the inversion, a quarter turn of the body is completed in order to stay close with the pole and reduce energy loss. Barlow (1973) found that it took an average of 0.695 seconds to get off of the top of the pole from the moment the pole touched the back of the plant box. Barlow (1973) also found that the average peak vertical extension force of the pole on the plant box was 247 pounds. The peak vertical extension increased as the bar increased in height.

The Fly Away

As the pole goes from bent back to straight, the vaulter implements another quarter turn as the energy from the pole propels the vaulter over the cross bar. Launder and Gormley (2008) explained that the top of the vault is a result of the previous phases and can be unique to the individual vault. Launder and Gormley (2008) also stated that the vaulter should attempt to drop the legs as soon as they are over the bar. This will push the center of gravity to the highest point over the bar.

Conceptual Framework

The Continuous Chain Model suggests that in order for the next phase of the vault to be successful, the previous phases need be performed correctly to progress forward. Barlow's (1973) study stated that from the moment the pole touches the back of the box, there is an average of 0.695 seconds until the vaulter is going vertically over the bar. There is very little time to make corrections. This is one of the reasons why the pole vault is so difficult. The take-off is an early phase in the pole vault and, when done correctly, the consecutive phases can happen ideally, leading to a bar clearance. When the take-off is done poorly the results, more often than not, result in a missed attempt due to poor energy transfer and poor positioning on the pole.

The Importance of the Take-off

The take-off in the pole vault is the most important phase in the pole vault (McGinnis, 2007). According to McGinnis, the take-off phase begins with the touchdown of the take-off foot and ends the instant the foot leaves the ground. The pole vault take-off is best demonstrated when looking at factors that determine performance.

$$PE(apex) = TE(to) + U(to\text{-}rel) - E(to\text{-}rel)_{lost} - KE(rel)_{xs}$$

where,

$PE(apex)$	=	potential energy of vaulter at the apex of vault
$TE(to)$	=	total mechanical energy of vaulter and pole at take-off
$U(to\text{-}rel)$	=	mechanical work done by vaulter from take-off to pole release
$E(to\text{-}rel)_{lost}$	=	mechanical energy lost from take-off to pole release
$KE(rel)_{xs}$	=	excess kinetic energy at pole release.

Figure 1. *Maximum Height Achieved by Pole Vaulter Using Physics (McGinnis, 2007)*

McGinnis (2007) explained:

> The equation essentially states that the maximum height achieved by a pole vaulter (PE [apex]) is determined by:
>
> 1. How high his center of gravity is and how fast he is moving at take-off (TE[to]).
>
> 2. How much he pulls and pushes himself upward on the pole during the vault (U[to-rel]).
>
> 3. How much energy is lost or not converted to potential energy (E[to-rel]lost and KE[rel]xs) (p. 1).

Research on the pole vault take-off found that higher-level pole vaulters possessed the ability to achieve greater running velocities, have a tall plant before the take-off, shorten their last stride preceding takeoff, increase horizontal velocity over the last three strides, have a shorter ground contact time at take-off, and have a high vertical velocity (Barlow, 1973; McGinnis, 2007; Gros, 1982; Launder & Gormley, 2008). Barlow (1973) found that braking force represented 66% of total time in contact with the ground of the take-off foot lasting an average of 0.080 seconds. The other 33% represented the total forward thrust force during contact time. Improving thrust force time during the take-off may increase the transfer of kinetic energy to elastic energy, thus improving the height of the pole vault.

Foot Placement During the Take-off (On, Under, and Out)

Taking off "on" in the pole vault is when the take-off foot is directly under the top hand. *In "From Beginner to Bubka" by* Launder and Gormley (2008), Vitaly Petrov, the coach of both Bubka and Isinbayeva, argued that the take-off point in the pole vault needs to be directly under the top hand during the jump. The importance occurs where the top hand is in relation to the take-off foot upon leaving the ground and not where the foot starts. The advantages of being "on" in the pole vault are, reduced loss of energy transfer, better take-off angle, better body position, faster pole speed, and greater pole bend (Launder & Gormley, 2008).

Taking off "under" in the pole vault is when the take-off foot is closer to the vault box than the top hand. Both coaches and athletes try to avoid taking off "under" due to the negative consequences. The negative consequences are a loss of energy, low take-off angle, bad body position, and slow pole speed, resulting in possible back injury (Launder & Gormley, 2008). There are successful elite pole vaulters who have jumped 6.00m or more and have taken off up to a foot under (Bussabarger, 2010). Pole vault is about transferring energy from kinetic to potential elastic energy. Barlow (1973) suggested that taking off under increases breaking force, thus losing energy. As of yet, no published research describes the difference between breaking forces and ground reaction force for taking off on, under, and out in the pole vault.

A pre-jump or a free take-off occurs when the vaulter takes off of the ground and the pole is still unloaded. The take-off foot would be directly under the top hand, but the pole tip would only touch the back of the box the instant the foot leaves the ground. The free take-off is part of the Petrov model and is practiced by Bubka and Isinbayeva, the world record holders in the event. Launder (1989) explained that there are many advantages to a free take-off. The advantages are that the vaulter is able to attack the plant more aggressively due to better body position, less energy loss, higher hand hold, and the use of stiffer poles, resulting in less pressure on the back of the vaulter. By attempting the free take-off vaulters reduce the rate of taking off under, which has many more negative consequences than positive. It is important to note that a free take-off and an out take-off overlap in the fact that the take-off foot is just behind that top hand when the pole is in the back of the box. The difference comes from how far the foot is away from an on take-off (the point where the top hand is directly over the take-off foot). Being too far out or away from an on take-off will not allow the pole vault pole to reach a vertical positioning. Instead, the pole will bend in a more horizontal motion, which can lead to dangerous outcomes. A free take-off usually refers to a vaulter taking-off outside two to four inches out from an on take-off.

Kinetics and Kinematics in the Take-off

Limited research exists regarding ground reaction forces during the pole vault take-off, although there is a plethora of long jump research. The kinematics of the pole vault take-off is often described in comparison to the long jump take-off (Plessa et al., 2010). Plessa et al. (2010) found that there was no significant difference between the pole vault take-off and the long jump take-off. Due to the findings of Plessa et al. (2010) and the lack of ground reaction force research on the pole vault take-off, it is important to include research on ground reaction force of the long jump take-off. Only two published studies have measured ground reaction forces of the pole vault take-off. This section will review the research, methods, and findings of Plessa et al. (2010) and Barlow (1973).

A recent study by Plessa et al. (2010) compared the take-off ground reaction force patterns of the pole vault and the long jump. The aim of the study was to determine if there is a similarity between the long jump and the pole vault take-off. If there are kinetic similarities, then long jump drills may be more beneficial for pole vaulters due to avoiding extra loading of a pole vault pole.

Researchers observed 12 right-handed female pole vaulters who competed in the national championships during the time of the study. Their mean highest vaults were 4.10 meters. Ground reaction forces were measured using a Kistler 9286AA force plate. The force plate was placed at the subject's optimal take-off location and covered with a tartan surface. A camera recording at 50Hz was used and Peak Performance software was utilized for two-dimensional kinetic analysis. Testing took place in an indoor simulated competition. After their individual 30 minute warm up, they completed four pole vault trials and four long jump trials.

Analysis of the data measured temporal force parameters for the vertical, anterior-posterior, and medial-lateral ground reaction force components. The temporal phases determined were the duration of the total contact time measured in milliseconds. Passive and active, breaking and propulsive, and medial and lateral phases were measured. Force parameters were the impulses during the temporal phases expressed in body weight. Time in peak force was calculated in milliseconds. Paired samples t-tests were used to measure the difference between the long jump and the pole vault.

The results show that the kinematic parameters had lower values for the pole vault than the long jump. These parameters included, angle of the support leg (57.4 vs. 60.1 deg), the touchdown horizontal running velocity of the center of mass (7.2 vs. 8.0 m/s), the take-off angle of the center of mass (19 vs. 22 deg), and the take-off resultant of the center of mass (6.4 vs. 7.3 m/s). Kinetic parameters examined for ground reaction force patterns were similar for the long jump and the pole however, contact time, and force and impulse magnitudes were significantly different ($p \leq .05$). One important factor is that the first part of the contact (passive and breaking) is the same duration while the second part of the contact phase (active and propulsive) was longer in duration during the long jump. Active was 9.5% shorter and propulsive was 15.3% shorter in the pole vault. Total contact time is a longer duration for the long jump than the pole vault take-off. Plessa et al. (2010) stated that pole vault improvements may occur by increasing the duration of the active and propulsive contact phase of the pole vault take-off.

Barlow (1973) conducted a comprehensive study, analyzing the kinetic and kinematic factors of the last step, the take-off, and the pendulum phases of pole vaulting. Barlow stated that kinetic factors affecting the pole vault are largely determined by many previous variables, up to the phase during which the vaulter clears the cross bar. Due to the substantial amount of data found during the study and the purpose of this literature review, the focus is primarily on the running approach and take-off.

Eleven vaulters ranging in age from 16 to 25 years volunteered for the study. All subjects were male and pole vaulted at the amateur, collegiate, or interscholastic level. Best recorded heights ranged from 4.27 to 5.50 meters. Barlow (1973) noted that all vaulters were considered to be highly capable performers. The research took place indoors on a tartan track surface. After completion of an appropriate warm up period, the athletes started vaulting at a cross bar six inches under their personal best heights. If the bar was cleared, the vaulter could move the bar three to six inches higher. Athletes were allowed at least seven jumps and no more than 10 jumps to clear the highest height possible.

Kinetic parameters were obtained from a 36 inch by 24 inch multi-dimensional force platform positioned to measure the final foot strike at take-off. The force plate was calibrated prior to the study to insure accuracy. The forces recorded were vertical force, horizontal braking force, and horizontal thrusting force. Kinematic parameters were studied through high speed cinematography. Of the 94 vaults that were recorded, 17 were successful and eight were considered almost successful. In total, 25 vaults ranging between 3.96m-5.33m were used for kinetic and kinematic analysis. Statistical package for the social science (SPSS) was used for statistical analysis. Barlow (1973) stated that the effectiveness of force on kinematic results depends on two things: the magnitude and the time for which it acts on the body. The recording oscillograph was able to analyze various periods of force within 0.001 of a second. Specific time phase measures during the run and take-off included: duration of foot contact at the take-off, horizontal breaking force duration, horizontal thrusting force duration, and pole plant completion in relation to the initiation of support during the take-off.

Kinematic results for the approach run showed that the last two to three strides may be shortened by as much as 0.2032 to 0.4572m in anticipation for the take-off. The majority of champion-level vaulters shortened their last strides by an average of five inches (Barlow, 1973). Notedly, vaulters who vaulted higher than 4.89m had longer stride lengths during their run, but their last three strides were shorter compared to the vaulters who jumped less than 4.89m.

Kinematic results for the pole plant suggest that the pole plant accounts for 50-75% of a successful vault. Barlow (1973) found vaulters who vaulted 4.89m or higher initiated their pole plant an average 3.65m before reaching take-off compared to vaulters who vaulted less than 4.89m who initiated their plant 3.29m before take-off. During the final three steps, vaulters who jumped higher than 4.89m increased speed during the first two steps and slowed down during the take-off step. For the vaulters who jumped less than 4.89m, deceleration occurred during all three steps on average. Barlow (1973) noted that 67% of all the trials resulted in an increase in horizontal displacement from the third to the second stride. Lastly, 75% of the higher vaulting group and only 16.7% of the lower vaulting group accelerated over the two strides.

Kinetics of the take-off movement is an explosive movement requiring maximal effort in a short duration. The take-off duration was generally less than 0.13 of a second for the study. Barlow (1973) believed that a short duration of the take-off is a highly important factor leading to high velocity of the body. The study found that the total average duration of horizontal and vertical force was 0.122 second. As the cross bar heights increased, the mean duration decreased. The ranges for horizontal and vertical duration ranged from 0.135 seconds at 3.96m to 0.116 seconds at 5.33m. Barlow (1973) concluded that better vaulters had shorter support times at take-off.

Horizontal striking force started the moment the support leg made contact with the force plate and lasted an average duration of 0.019 second. Propulsive muscular effort was recorded when the entire foot was flat on the force plate and the center of gravity was directly over the support leg. The average peak vertical force at the take-off occurred at 0.045 second after the first point of contact. Horizontal breaking force accounted for 66% of total time the vaulter’s support leg was in contact with the force plate. The average peak horizontal breaking force was recorded at 0.015 second after first contact. The total mean value for breaking force duration was 0.080 seconds. On the contrary, horizontal thrusting force accounted for 33% of total contact time and was first reached at 0.100 second after initial contact or 0.022 second before take-off.

A few take-off kinematic findings of study included, better performers in every case had faster running speed. All vaulters shortened their last preceding take-off from 2.04 to 4.20 inches. The length of the second stride tended to be greater than the third or last stride of the last three steps. All vaulters decreased speed in the final stride of take-off, but better vaulters increased speed in their first to second stride and decreased speed from second to last stride. Higher performers were able to increase their speed longer than lower performers. Pole plants were initiated 0.432 to 0.408 seconds before take-off. Lastly, the average pole plant took place 1.87 strides before take-off.

A few take-off kinetic findings of the study included the average duration of forces at the take-off foot was 0.122 second in all vaults and shorter durations were found for higher performers compared to lower performers. Horizontal breaking force accounted for 66% of total time, averaging 0.080 second and propulsive force accounted for 33%. Peak vertical striking force at take-off had an average magnitude of 819 pounds during the first 0.01 to 0.02 of a second (approximately five times the body weight of the vaulter), peak vertical propulsive force averaged 500 pounds (approximately three times the vaulter's body weight), and average breaking force was 607 pounds compared to 56 pounds for horizontal thrusting force. Lastly, the total average vertical impulse at take-off was 57.89 pounds-second. The athletes who vaulted 4.89m or better proved to be more efficient in changing their momentum while in contact with the force plate. Barlow (1973) found that peak vertical striking force tended to increase as the cross bar increased. Horizontal breaking force and vertical impulses are found to be greater for the more successful vaulting group. Due to different body mass, the researchers divided vertical impulse by the vaulter's mass to compare more accurate readings.

Conclusion

The pole vault is an extremely complex sport that involves many different variables. There has been a lot of research to try to understand the sport and its variables in order to create better athletes and consistent performances. The continuous chain model discusses the importance of the phases of the pole vault and how each phase builds on the previous phase. The take-off phase is one of the earliest phases of the pole vault and has been researched the most. Most research on this phase measures take-off angles and speed during the final three strides of the approach run. Researchers agree that the take-off is the most important phase of the pole vault. Yet, there have only been two articles measuring ground reaction forces of the take-off leg and Barlow's (1973) research is over 30 years old. Plessa et al. (2010) published their study more recently, but neither of the two articles or any research has commented on the ground reaction force of the take-off in relation to being on, under, or out.

CHAPTER 3. METHODOLOGY

Participants

Fifteen healthy male and female division one college pole vaulters and multi-event athletes from North Dakota State University (NDSU) volunteered to participate in the study. Seven of those athletes met the criteria of having five or more jumps in at least two of the three categories of out, on, and under during the study. At the time of the study, their personal best vaults range between 3.8 meters and 5.11 meters. Vaulters height, weight, personal best heights, six step approach length, pole, and take-off were recorded in a data history form. All of the subjects were right-handed pole vaulters who take-off with their left foot. Approval from the North Dakota State University Institutional Review Board was obtained.

Testing Procedures

Athletes vaulted indoors on a raised pole vault runway during normal practice sessions. The environmental conditions were ideal for the study. Five vault practices were used for testing with individual athletes being tested for a maximum of four practices. The vaulters were allowed their normal warm up routine and testing started when the vaulters got back to their 12 step approach run. Demographic data was collected prior to the testing. Each vaulter vaulted through the testing procedures like a normal practice. Only jumps during which the vaulter was able to complete a full jump, swing to vertical, and make an attempt at a bungee was analyzed. The bungee height was placed at a height of six inches over the subject's personal best height. Before each vault, the force plate was zeroed out and the subject checked their on step where the top hand of the vaulter is directly above the take-off foot as shown in Figure 2. Subjects on steps were tested by standing on the ball of their take-off foot and having their top hand directly over their take-off foot. The vaulters weight was recorded with AMTI Accupower software (Advanced Mechanical Technology Inc, Watertown, MA, USA) and video record of the on step was recorded with Dartfish software (Version 5, Alpharetta, Georgia, USA). No more than 10 jumps and no fewer than five jumps were collected from each vaulter at each of their four practices. All the jumps were organized into categories of on, under and out.

Data Collection

Ground reaction forces were measured using a 40 in width x 30 in length x 4.9 in height AMTI Accupower (Advanced Mechanical Technology Inc, Watertown, MA, USA) force plate at a sampling rate of 2,400 Hz using Accupower software. The force plate was fixed in an 11 inch tall, three foot-eleven inch wide raised runway between 3.048m and 3.9624m from the back of the box. The top board is 1 1/8th tung and groove sturdifloor and the bottom brackets are 2 ½ x 9 ½ I-joist eight inch sections. A tartan surface was placed over the runway and the force plate so the force plate was level with the raised runway. All trials were recorded with a Sony DCR-HC52 video camera filming at 30 frames per second. The camera was set from a distance of 11 meters on the right side of the runway from the center of the force plate and at a camera height of 1.6 meters. Three lines were placed on the runway at 2.74m, 3.05m, and 3.96m from the back of the vaulting box for the use of reference points of the Dartfish software.

Data Analysis

Vaults were randomly selected by order of statistical importance to reach an effect size of 40. Nine jumps were selected from the pool of vaulters who had at least three vaults in all three jumping groups. Six jumps were selected from the pool of vaulters who had at least one jump in all three groups. The remaining jumps were selected from a pool of vaulters with at least five jumps in 2 or more groups. Out of the 226 jumps collected from seven subjects, 24 of 24 outs, 42 of 54 ons, and 42 of 66 unders were used. There were 82 attempts in which the athletes made no attempt or data was not collected.

Dartfish software was used to determine the difference between the subjects on step and take-off step in meters. On steps were measured prior to the vault attempt and marked as zero, shown in Figure 2. On jumps were defined as having a range 0±.0254m, out jumps were any jumps greater than .0254m from the on step, and under steps were jumps that were less than on 0.0254m of the on step, shown in Figure 3.

Figure 2. *The vaulter checking the on step. The on step is marked at 129 inches, or 3.2766m. For this jump, 3.2766 meters is marked at zero to show that jumps greater than zero are positive and jumps less than zero are negative.*

Figure 3. *The vaulter's take-off step at 131 inches or 3.3274m which is 0.0508m greater than zero. Since 0.0508m is greater than 0.0254m this jump is placed into the out category.*

Ground reaction force parameters were consistent with the study by Plessa et al. (2010), in which vertical (Fz), anterior-posterior (Fy), and medio-lateral (Fx) were collected in newtons and were converted to body weight. Total contact time was expressed as anterior-posterior (tFy), and was measured in milliseconds. Temporal phases were the duration of the contact phase ($t_{contact}$) and measured in milliseconds and will also be similar to Plessa et al. (2010). Breaking phase will be measured using ($t_{breaking}$) and the propulsive ($t_{propulsive}$) phase ($t_{breaking}$: from $t_{contact}$ initiation until Fy changed from negative to positive and t propulsive: from $t_{breaking}$ ending until $t_{contact}$ ending) (Plessa et al., 2010, p. 419). Lastly the force parameters were the magnitudes of Fz, Fy+, Fy-, Fx+, and Fx- peaks expressed in body weight, as shown in Figure 4.

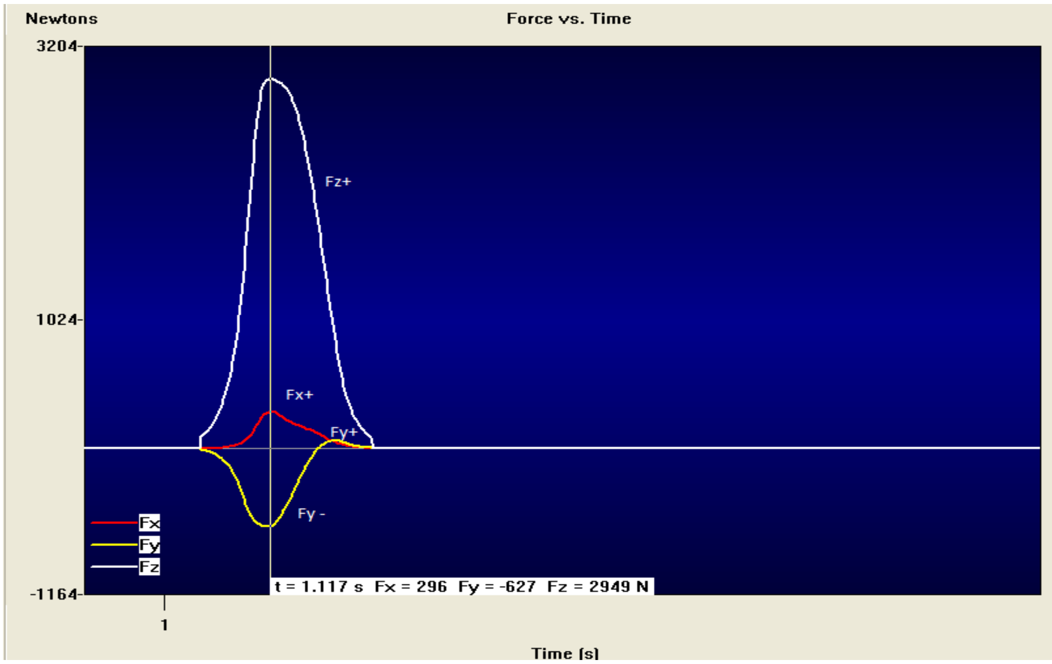

Figure 4. *Force data of Fz vertical force, Fy- anterior breaking force, Fy+ propulsive posterior force, Fx- medial, and Fx+ lateral force using Accupower*

Statistical Analysis

All information and test scores were entered into Statistical Analysis Software (SAS Institute Inc. 2011. SAS/STAT 9.3 User's Guide. Cary, NC: SAS Institute Inc.). A p-value $\leq$ 0.05 was used to determine statistical significance. Separate mixed model ANOVAs were run on each outcome measure with jump type (group) and vaulter (subject) treated as fixed effects and the individual jumps treated as random effects. We then obtained F-tests on groups and subjects and ran follow up t-tests on the least-squares means (LS-means) for all significant F-tests. The tests compared: vertical force, breaking force, propulsive force, medial force, lateral force, total time on the force plate, time breaking, and time propulsive for all jumps that were on, under and out.

CHAPTER 4. MANUSCRIPT FOR PUBLICATION FOR TRACK COACH

Introduction

The take-off is regarded as the most important phase in the pole vault. There is an extensive amount of research on pole vault velocity, take-off angles, and their effects on maximum vertical height. Little information exists regarding ground reaction force. During a literature search, two articles found measure ground reaction force and ground contact time of the take-off leg in the pole vault: one by Barlow (1973) and one by Plessa et al. (2010). Numerous pole vault techniques emerged since the late 1940s when fiberglass poles were introduced. Vital Petrov and his creation of the Petrov/Bubka pole vault model produced world records in the pole vault for both men and women. Alan Launder, in his book *From Beginner to Bubka,* discussed the Petrov model in detail.

A popular theory of the Petrov model is the free take-off. A free take-off is when the vaulter takes off while the pole remains unloaded (Launder & Gormley, 2008). The take-off foot is just behind the top hand the moment the foot leaves the ground. There is some confusion with the terminology since free take-off, pre jump, and out take-off have been used interchangeably. (For the purpose of this discussion, the term out take-off will be used.) The theory suggests that by taking off slightly further away from the vault box instead of directly under the top hand, less energy will be lost and the vaulter will be in a better position for the next phase of the vault. As of yet, no published studies have measured the difference in ground reaction force of the take-off when the vaulter takes off on, under, or out in the pole vault.

The purpose of this study is to compare the differences in ground reaction forces between pole vault take-offs that are out, on and under. The science of pole vault can be described using physics, kinematics, and kinetics. The pole vault involves the transfer of kinetic energy into gravitational potential energy or vertical height (Pelletier, 2011). Kinetic energy is defined as “Energy due to the motion of an object” (McGinnis, 2005, p. 392). Elastic potential energy or strain energy is defined as “Energy due to the deformation of an object; for stretching or compromising” (McGinnis, 2005, p. 395). Gravitational potential energy is energy of a body or system due to gravitational force. A full pole vault involves all three energy transfers. The pole vaulter builds up kinetic energy by sprinting down the runway. As the pole vaulter plants the pole in the box, the kinetic energy is transferred to the pole creating elastic potential energy. The fiber glass pole bends while lifting the vaulter vertically into the air, transferring the kinetic energy to gravitational potential energy, or maximum force against gravity (Pelletier, 2011).

Technical

There are six basic phases of the pole vault. These phases include the run, the plant, the take-off, the swing, the inversion, and the fly away. Each phase needs to work together to create a pole vault. The continuous chain model suggests that each phase of the pole vault builds the previous phrase. If a vaulter builds up a great amount of speed or kinetic energy during the run up phase, but the take-off was poor, energy will be lost during the take-off. The energy loss cannot be recovered during the following phases (Young, 2002).

Barlow's (1973) study stated that from the moment the pole touches the back of the box, there is an average of .695 seconds until the vaulter is going vertically over the bar.

There is very little time to make corrections. This is one of the reasons why the pole vault is so difficult. The take-off is an early phase in the pole vault and, when done correctly, the next phases can happen, ideally leading to a bar clearance. When the take-off is done poorly, the results more often than not result in a missed attempt due to poor energy transfer and poor positioning on the pole.

The Take-off

The take-off in the pole vault is the most important phase in the pole vault (McGinnis, 2007). According to McGinnis (2007), the take-off phase begins with the touchdown of the take-off foot and ends at the instant that the foot leaves the ground. Research on the pole vault take-off found that higher-level pole vaulters possessed the ability to achieve greater running velocities, have a tall plant before the takeoff, shorten their last stride preceding takeoff, increase horizontal velocity over the last three strides, have a shorter ground contact time at take-off, and have a high vertical velocity (Barlow, 1973; McGinnis, 2007; Gros, 1982; Launder & Gormley, 2008). Barlow (1973) found that breaking force represented 66% of total time in contact with the ground of the take-off foot, lasting an average of .080 seconds. The other 33% represented the total forward thrust force during contact time. Improving thrust force time and reducing ground contact time during the take-off may increase the transfer of kinetic energy to elastic energy, thus improving the height of the pole vault.

The kinematics of the pole vault take-off is often described in comparison to the long jump take-off (Plessa et al., 2010). Plessa et al. (2010) found that there was no significant difference between the pole vault take-off and the long jump take-off. Due to the findings of Plessa et al. (2010) and the lack of ground reaction force research on the pole vault take-off, it is important to include research on ground reaction force of the long jump take-off.

The results of Plessa et al. (2010) demonstrated that kinetic parameters for ground reaction force patterns were similar for the long jump and the pole vault however, contact time and force and impulse magnitudes were significantly different. One important factor is that the first part of the contact phase (passive and breaking) is the same duration, while the second part of the contact phase (active and propulsive) were longer in duration during the long jump. Active was 9.5% shorter and propulsive was 15.3% shorter in the pole vault. Total contact time is longer in duration for the long jump take-off than the pole vault take-off. Plessa et al. (2010) stated that increasing the duration of the active and propulsive contact phase of the pole vault take-off could lead to improvements in pole vault performance.

The take-off duration was generally less than 0.13 of a second for the study. Barlow (1973) believed that a short duration of the take-off is a highly important factor leading to high velocity of the body. The study found that the total average duration of horizontal and vertical force was .0122 second. As the cross bar heights increased, the mean duration decreased. The ranges for horizontal and vertical duration ranged from 0.135 seconds at 3.96 to 0.116 seconds at 5.33m. Barlow (1973) concluded that better vaulters had shorter support times at take-off.

Take-off kinetic findings of the study included the average duration of forces at the take-off foot was 0.122 second in all vaults and shorter durations were found for higher performers compared to lower performers. Horizontal breaking force accounted for 66% of total time averaging 0.080 second and propulsive force accounted for thirty-three percent. Peak vertical striking force at take-off had an average magnitude of 819 pounds during the first 0.01 to 0.02 of a second (approximately five times the vaulter's body weight), peak vertical propulsive force averaged 500 pounds (approximately three times the body weight of the vaulter), and average breaking force was 607 pounds, compared to 56 pounds for horizontal thrusting force. Lastly, the total average vertical impulse at take-off was 57.89 pounds-second. Those athletes who vaulted 4.89m or better were found to be more efficient in changing their momentum while in contact with the force plate. Barlow (1973) found that peak vertical striking force tended to increase as the cross bar increased. Horizontal breaking force and vertical impulses are found to be greater for the more successful vaulting group. Due to different body mass the researchers divided vertical impulse by the vaulter's mass to compare more accurate readings.

Methodology

Participants

Fifteen healthy male and female division one college pole vaulters and multi-event athletes from North Dakota State University (NDSU) volunteered to participate in the study. Seven of those athletes met the criteria of having five or more jumps in at least two of the three categories of out, on, and under during the study. At the time of the study, their personal best vaults range between 3.8 meters and 5.11 meters. Vaulter's height, weight, personal best heights, six step approach length, pole, and take-off were recorded in a data history form. All of the subjects were right-handed pole vaulters who take-off with their left foot. Approval from the North Dakota State University Institutional Review Board was obtained.

Testing Procedures

Athletes vaulted indoors on a raised pole vault runway during normal practice sessions. The environmental conditions were ideal for the study. Five vault practices were used for testing with individual athletes being tested for a maximum of four practices. The vaulters were allowed their normal warm up routine and testing started when the vaulters got back to their 12 step approach run. Demographic data was collected prior to the testing. Each vaulter vaulted through the testing procedures like a normal practice. Only jumps in which the vaulter was able to complete a full jump, swing to vertical, and make an attempt at a bungee were analyzed. The bungee height was placed at a height of six inches over the subject's personal best height. Before each vault, the force plate was zeroed out and the subject checked his or her on step. Subjects on steps were tested by standing on the ball of their take-off foot and having their top hand directly over their take-off foot. The vaulter's weight was recorded with AMTI Accupower software (Advanced Mechanical Technology Inc, Watertown, MA, USA) and video record of the on step was recorded with Dartfish software (Version 5, Alpharetta, Georgia, USA). No more than 10 jumps and no fewer than five jumps were collected from each vaulter at each of their four practices. All the jumps were organized into categories of on, under, and out.

Data Collection

Ground reaction forces were measured using a 40 in width x 30 in length x 4.9 in height AMTI Accupower force plate (Advanced Mechanical Technology Inc, Watertown, MA, USA) at a sampling rate of 2,400 Hz using Accupower software. The force plate was fixed in an 11 inch tall three foot eleven inch wide raised runway between 3.048m and 3.9624m from the back of the box. The top board is 1 1/8th tung and groove sturdifloor and the bottom brackets are 2 ½ x 9 ½ I-joist eight inch sections. A tartan surface was placed over the runway and the force plate so the force plate was level with the raised runway. All trials were recorded with a Sony DCR-HC52 video camera filming at 30 frames per second. The camera was set from a distance of 11 meters on the right side of the runway from the center of the force plate and at a camera height of 1.6 meters. Three lines were placed on the runway at 2.74m, 3.05m, and 3.96m from the back of the vaulting box for the use of reference points of the Dartfish software.

Data Analysis

Vaults were randomly selected by order of statistical importance to reach an effect size of 40. Nine jumps were selected from the pool of vaulters who had at least three vaults in all three jumping groups. Six jumps were selected from the pool of vaulters who had at least one jump in all three groups. The remaining jumps were selected from a pool of vaulters with at least five jumps in 2 or more groups. Out of the 226 jumps collected from seven subjects, 24 of 24 outs, 42 of 54 ons, and 42 of 66 unders were used. There were 82 attempts that the athletes made no attempt or data was not collected.

Dartfish software was used to determine the difference between the subjects on step and take-off step in meters. On steps were measured prior to the vault attempt and marked as zero, shown in Figure 5. On jumps were defined as having a range 0±.0254m, out jumps were any jumps greater than .0254m from the on step, and under steps were jumps that were less than on .0254m of the on step, shown in Figure 6.

Figure 5. *The vaulter is checking the on step which is marked at 129 inches or 3.2766m. For this jump, 3.2766 meters is marked at zero to show that jumps greater than zero are positive and jumps less than zero are negative.*

Figure 6. *The vaulter's take-off step at 131 inches or 3.3274m which is .0508m greater than zero. Since .0508m is greater than .0254m this jump is placed into the out category.*

Ground reaction force parameters were consistent with Plessa et al. (2010), in which vertical (Fz), anterior-posterior (Fy), and medio-lateral (Fx) were collected in newtons and were converted to body weight. Total contact time was expressed as anterior-posterior (tFy), and was measured in milliseconds. Temporal phases were the duration of the contact phase ($t_{contact}$) and measured in milliseconds and will also be similar to Plessa et al. (2010). Breaking phase will be measured using ($t_{breaking}$) and the propulsive ($t_{propulsive}$) phase ($t_{breaking}$: from $t_{contact}$ initiation until Fy changed from negative to positive and t propulsive: from $t_{breaking}$ ending until $t_{contact}$ ending) (Plessa et al., 2010, p. 419). Lastly, the force parameters were the magnitudes of Fz, Fy+, Fy-, Fx+, and Fx- peaks expressed in body weight as shown in Figure 7.

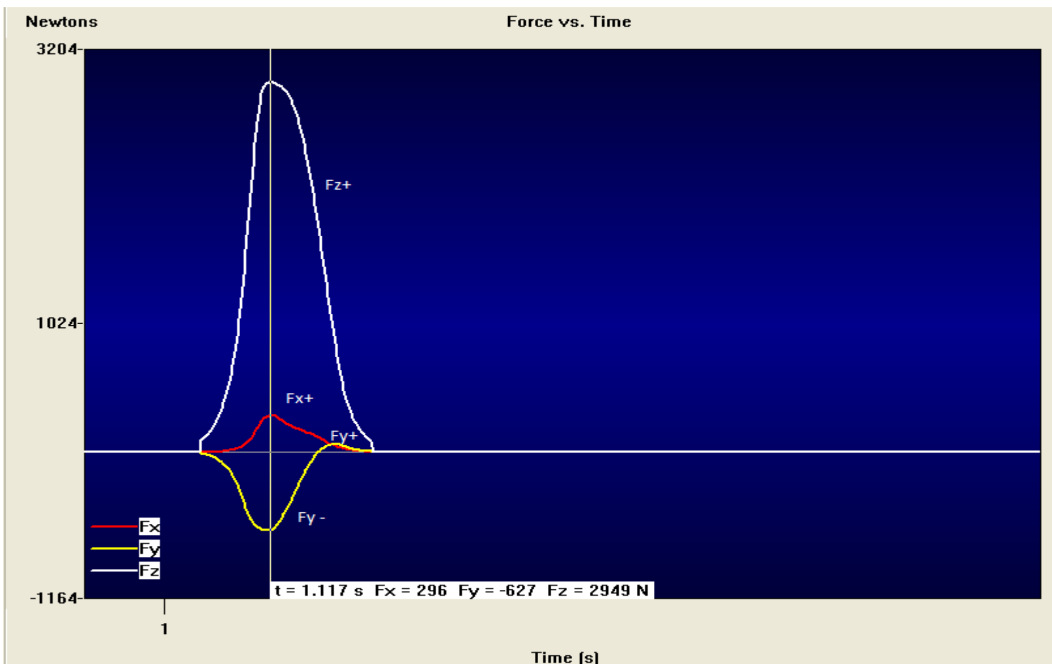

Figure 7. *Force data of Fz vertical force, Fy- anterior breaking force, Fy+ propulsive posterior force, Fx- medial, and Fx+ lateral force using Accupower*

Statistical Analysis

All information and test scores were entered into Statistical Analysis Software (SAS Institute Inc. 2011. SAS/STAT 9.3 User's Guide. Cary, NC: SAS Institute Inc.). A p-value $\leq$ 0.05 was used to determine statistical significance. Separate mixed model

ANOVAs were run on each outcome measure with jump type (group) and vaulter (subject) treated as fixed effects and the individual jumps treated as random effects. We then obtained F-tests on groups and subjects and ran follow up t-tests on the least-squares means (LS-means) for all significant F-tests. The tests compared vertical force, breaking force, propulsive force, medial force, lateral force, total time on the force plate, time breaking, and time propulsive in jumps that are on, under and out.

Results

Means and standard deviation are listed in Table 1. No significant differences ($p>0.05$) were found between take-offs that are out, on, and under in force parameters Vertical Fz Posterior Fy, Anterior Fy, Lateral Fx, and Medial Fx. Time parameters of Tcontact, Tbreaking, and Tpropulsive were not found to be significant between jumps that were on, under, and out. Significant differences were found between subjects for all categories. Table 2 demonstrates the effect of each variable between the three jumping groups and between subjects.

Discussion

The findings are consistent with Barlow (1973) and Plessa et al. (2010). Although no significant differences were found between the different jump types, it is important to note that Anterior Fy, Tbreaking, and Tpropulsive were the closest to significance. Other observations included

1. Vertical Fz force increased the from take-offs out to under
2. Posterior Fy (Breaking) force increased from take-offs out to under

3. Anterior Fy (Propulsive) force decreased from take-offs out to under

4. Total contact time increased from take-offs out to under

5. Total breaking time decreased from take-offs out to under

Table 1. *Mean and Standard Deviation of Out, On, and Under Take-offs*

Mean and Standard Deviation						
Forces (BW)	Out	±	On	±	Under	±
Vertical FZ	3.591	0.496	3.856	0.390	3.939	0.435
Posterior Fy B	-0.879	0.169	-1.009	0.198	-1.087	0.211
Anterior Fy P	0.157	0.036	0.135	0.043	0.118	0.037
Lateral Fx R	0.286	0.138	0.380	0.170	0.407	0.172
Medial Fx L	-0.009	0.012	-0.009	0.022	-0.014	0.032
Time (ms)	Out	±	On	±	Under	±
Tcontact	0.190	0.019	0.192	0.029	0.198	0.016
Tbreaking	0.126	0.011	0.133	0.010	0.138	0.013
Tpropulsive	0.058	0.011	0.059	0.009	0.053	0.010

Table 2. *Difference Between Groups and Subjects*

Difference between Groups			Difference between subjects	
Forces (BW)	F Value	P Value	F Value	P Value
Vertical Fz	0.54	0.65	18.94	<.0001
Posterior Fy B	2.34	0.30	62.92	<.0001
Anterior Fy P	18.65	0.05	25.28	<.0001
Lateral Fx R	0.85	0.54	34.68	<.0001
Medial Fx L	0.58	0.63	12.21	<.0001
Time (ms)	F Value	P Value	F Value	P Value
Tcontact	0.75	0.57	6.4	<.0001
Tbreaking	4.39	0.19	45.79	<.0001
Tpropulsive	9.25	0.10	12.99	<.0001

Barlow (1973) observed that duration of total contact time was less for athletes who achieved greater vaulting success. The take off locations are unknown in Barlow (1973), but one can only speculate if the vaulters were taking off under or if other factors were affecting the data, such as speed and athletic strength. Barlow (1973) and Plessa et al. (2010) observed that 66% of total contact time is breaking force and the remaining 44% being propulsive force. The findings are consistent with this study: out take-offs represented 66.3%, on take offs represented 69.3% and under take-offs represented 69.7% of breaking force. These findings show that taking off further out increase the amount of propulsive time during the vault.

Slight force differences between studies can be attributed to the force plate being placed in a raised runway, resting on top of wood instead of a tartan surface. McGinnis (1989) stated that it can take more than 15 years for athletes to become proficient in the pole vault. During the testing procedure, it was observed that upper-class athletes were more consistent with their take off being on or out, whereas the underclassmen were consistently under. Of the seven subjects used, only two participated in the sport for fewer than five years. Vaulters in this study ranged in personal best heights from 3.8 meters to 5.11 meters, compared to Barlow (1973), 3.9 m to 5.50 m.

The difference in skill level may have attributed to some of the kinematic and kinetic difference. Ideally, the three jumping groups would be tested within individual subjects. Unbalanced data and lack of subjects made this impractical. Future research may include testing kinematic and kinetic ground force reactions of jumps that are on, under, and out within subjects.

As of now, this study was the first of its kind to test the differences between jumps that are out, on, and under. Due to the lack of research on the topic, it was difficult to determine what is significant in time and force between the take off types. According to Plessa et al. (2010), the differences between pole vault and long jump take offs .008 in Tcontact and .1 in AnteriorFy is significant, which is why these parameters were utilized for the study. A mixed modal statistical analysis was used to provide more accurate statistical analysis of the unbalanced data.

The limited significance between the jumping types was surprising due to the popularity of the Russian style of vaulting and the success the model has achieved. Although the study did not produce significant results, it does not mean that it does not matter where the vaulter takes off. The continuous chain theory states that each phase of the pole vault builds upon the previous phase. The pole vault is about building up energy and transfer of that energy. This study found that taking off on or out results in longer propulsive force, which put more energy into the chain. A proper take off places the vaulter in a better position to attain the next progression of the vault (Launder & Gormley, 2008).

Future research may include testing kinematic and kinetic ground force reactions of jumps that are on, under and out within subjects. One could also argue against the generalization of older, more skilled vaulters. Nonetheless, the findings were consistent with Barlow (1973) who used amateur and elite males and Plessa et al. (2010) who observed females who competed at a national level.

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CHAPTER 5. SUMMARY

Conclusion

The findings are important because there is little to no research on pole vault ground force reactions and take off location. Although statistically significant differences were not found in this study, Anterior Fy, Tbreaking, and Tpropulsive, are found to be close to significant. Correlations between Vertical Fz, Posterior Fy, Anterior Fy, Tcontact, and Tbreaking, and the take-off location may be useful in determining which vaulting technique is used by a coach and/or athlete. It is important to remember that force and time at the take off are only a part of pole vault chain. Even though no significance was found, one or more variables tested may be important enough to influence future phases of the pole vault. The study provides scientific information of time and forces at different take off locations instead of theory or speculation.

Limitations of the study include the unbalanced data and lack of “out” data. Ideally, the three jumping groups would be tested within individual subjects. Six of the seven participants were male, which makes the study difficult to generalize to females. Lastly, higher-skilled athletes may produce different results.

Recommendations

Future research may include testing kinematic and kinetic ground force reactions of jumps that are on, under, and out within subjects. Research on how the different take-offs affect the energy transfer into the pole would further improve our knowledge between the take-off and pole relationship. One could also argue against the generalization of older, more skilled vaulters. None the less, the findings were consistent with Barlow (1973) who used amateur and elite males and Plessa et al. (2010) who observed females who competed at a national level. A sample of elite pole vaulters may yield different findings.

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APPENDIX A. SUBJECT DATA COLLECTION

Date:________________ Test Day#: _________________

Subject No. :_______________ Name:(Last,First)______________________________

School/ Address: ____________________________________

____

____

Phone #:(_____)__________________________________

ANTHROPOMETRIC DATA

Age:____________ Weight:______________ LBS ____________KG

Birth Date:____________ Height:______________ Sex:___________

POLE SPECIFICATIONS

Manufacturer:______________________

BEST COMPETITIVE VAULT

Feet:__________________ Inches:______________________

LENGTH OF 12 STEP APPROACH RUN

Feet:__________________ Inches:______________________

MISCELLANEOUS COMMENTS

____

____

____

____

____

____

APPENDIX B. CINIMATIC AND PERFORMANCE CHARACTERISTICS OF SUBJECTS

Subject No.______________ Name:____________________________ Pole Vault Data

<u>SESSION 1</u>

1. Dartfish#__________ Accupower#_____________ On-step_________ Pole:Length________ Flex#_________ Take-off:____________
2. Dartfish#__________ Accupower#_____________ On-step_________ Pole:Length________ Flex#_________ Take-off:____________
3. Dartfish#__________ Accupower#_____________ On-step_________ Pole:Length________ Flex#_________ Take-off:____________
4. Dartfish#__________ Accupower#_____________ On-step_________ Pole:Length________ Flex#_________ Take-off:____________
5. Dartfish#__________ Accupower#_____________ On-step_________ Pole:Length________ Flex#_________ Take-off:____________
6. Dartfish#__________ Accupower#_____________ On-step_________ Pole:Length________ Flex#_________ Take-off:____________
7. Dartfish#__________ Accupower#_____________ On-step_________ Pole:Length________ Flex#_________ Take-off:____________
8. Dartfish#__________ Accupower#_____________ On-step_________ Pole:Length________ Flex#_________ Take-off:____________
9. Dartfish#__________ Accupower#_____________ On-step_________ Pole:Length________ Flex#_________ Take-off:____________
10. Dartfish#__________ Accupower#_____________ On-step_________ Pole:Length________ Flex#_________ Take-off:____________

SESSION 2

11. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________
12. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________
13. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________
14. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________
15. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________
16. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________
17. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________
18. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________
19. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________
20. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________

SESSION 3

21. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________

22. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________

23. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________

24. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________

25. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________

26. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________

27. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________

28. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________

29. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________

30. Dartfish#__________ Accupower#____________ On-step_________ Pole:Length________ Flex#_________ Take-off:___________

SESSION 4

31. Dartfish#_________ Accupower#___________ On-step________ Pole:Length_______ Flex#________ Take-off:__________

32. Dartfish#_________ Accupower#___________ On-step________ Pole:Length_______ Flex#________ Take-off:__________

33. Dartfish#_________ Accupower#___________ On-step________ Pole:Length_______ Flex#________ Take-off:__________

34. Dartfish#_________ Accupower#___________ On-step________ Pole:Length_______ Flex#________ Take-off:__________

35. Dartfish#_________ Accupower#___________ On-step________ Pole:Length_______ Flex#________ Take-off:__________

36. Dartfish#_________ Accupower#___________ On-step________ Pole:Length_______ Flex#________ Take-off:__________

37. Dartfish#_________ Accupower#___________ On-step________ Pole:Length_______ Flex#________ Take-off:__________

38. Dartfish#_________ Accupower#___________ On-step________ Pole:Length_______ Flex#________ Take-off:__________

39. Dartfish#_________ Accupower#___________ On-step________ Pole:Length_______ Flex#________ Take-off:__________

40. Dartfish#_________ Accupower#___________ On-step________ Pole:Length_______ Flex#________ Take-off:_________

APPENDIX C. RAW FORCE DATA

Table C1. *Force Data for "Out" Pole Vaults*

Group	Name	BW (N)	Onstep	Takeoff	Difference	Force#	Verticalfz	AnteriorfyP	PosteriorfyB	MedialfxL	Lateralfxr
1.000	JM-29-30	734.250	3.760	3.840	0.080	D4JM5	3.650	0.161	-0.782	0.000	0.202
1.000	JM-52-53	734.250	3.630	3.810	0.180	D4JM8	3.846	0.123	-0.722	-0.012	0.158
1.000	JM-62-63	734.250	3.680	3.760	0.080	D3JM3	3.636	0.121	-0.812	0.000	0.221
1.000	NB-69-70	756.500	3.660	3.710	0.050	D3NB6	4.180	0.147	-1.207	0.000	0.456
1.000	NB-9-10	756.500	3.680	3.760	0.080	D4NB1	4.218	0.161	-1.169	0.000	0.545
1.000	NB-74-75	756.500	3.680	3.730	0.050	D1NB9	4.135	0.120	-1.293	0.000	0.493
1.000	KF-71-72	658.600	3.630	3.710	0.080	D4KF5	3.362	0.162	-0.800	0.000	0.457
1.000	KF-157-1	658.600	3.250	3.380	0.130	D2KF11	3.410	0.200	-0.802	0.000	0.310
1.000	KF-212-2	658.600	3.230	3.280	0.050	D2KF15	3.315	0.200	-0.689	-0.005	0.275
1.000	JB-43-44	765.400	3.810	3.910	0.100	D2JB15	3.626	0.180	-0.885	0.000	0.280
1.000	AM-3-4	556.250	3.120	3.250	0.130	D2AM12	3.004	0.090	-0.992	-0.020	0.246
1.000	JM-52-53	734.250	3.630	3.840	0.210	D3JM2	3.564	0.125	-0.917	0.000	0.182
1.000	JM-3-4	734.250	3.660	3.840	0.180	D1JM2	3.713	0.166	-0.819	-0.004	0.328
1.000	JM-78-79	734.250	3.730	3.810	0.080	D2JM12	3.732	0.108	-1.050	0.000	0.225
1.000	JM-84-85	734.250	3.660	3.710	0.050	D3JM5	3.965	0.120	-0.847	0.000	0.624
1.000	AM-5	556.250	3.120	3.250	0.130	D2AM13	4.275	0.151	-0.949	-0.022	0.200
1.000	AM-8-9	556.250	3.120	3.180	0.060	D2AM14	4.020	0.106	-0.980	-0.011	0.307
1.000	WL-185-1	867.750	3.610	3.810	0.200	D2WL3	2.788	0.194	-0.799	-0.021	0.092
1.000	WL-203-2	867.750	3.610	3.680	0.070	D2WL5	2.903	0.198	-0.678	-0.045	0.129
1.000	WL-228-2	867.750	3.580	3.780	0.200	D2WL8	4.390	0.187	-0.686	-0.003	0.221
1.000	WL-11-12	867.75	3.53	3.71	0.18	D3WL6	2.97	0.19	-0.80	-0.02	0.22
1.000	WL-216-217	867.75	3.56	3.78	0.23	D2WL6	2.92	0.20	-0.73	-0.01	0.20
1.000	WL-38-39	867.75	3.58	3.68	0.10	D3WL6	2.97	0.19	-0.80	-0.02	0.22

Table C2. *Force Data for "On" Pole Vaults*

Group	Name	BW (N)	Onstep	Takeoff	Difference	Force#	Verticalfz	AnteriorfyP	PosteriorfyB	MedialfxL	Lateralfxr	Tcontact
2.000	JM-13-14	734.250	3.810	3.810	0.000	D1JM5	3.762	0.147	-0.927	0.000	0.208	0.190
2.000	JM-42-43	734.250	3.730	3.760	0.030	D3JM1	2.699	0.108	-0.910	0.000	0.403	0.186
2.000	JM-88-89	734.250	3.810	3.780	-0.030	D2JM14	3.764	0.131	-0.753	0.000	0.456	0.193
2.000	NB-33-34	756.500	3.630	3.610	-0.020	D1NB4	4.438	0.087	-1.470	0.000	0.582	0.214
2.000	NB-91-92	756.500	3.630	3.610	-0.020	D2NB12	4.239	0.107	-1.293	0.000	0.601	0.210
2.000	NB-82-83	756.500	3.630	3.610	-0.020	D3NB7	4.169	0.110	-1.268	0.000	0.486	0.213
2.000	KF-66-68	658.600	3.380	3.350	-0.030	D4KF2	3.433	0.197	-0.750	0.000	0.325	0.190
2.000	KF-37-38	658.600	3.280	3.300	0.020	D1KF2	3.272	0.109	-0.923	0.000	0.328	0.197
2.000	KF-59-60	658.600	3.280	3.300	0.020	D1KF4	3.245	0.182	-0.750	0.000	0.275	0.191
2.000	JB-68-69	765.400	3.780	3.760	-0.020	D2JB19	3.969	0.154	-1.040	0.000	0.466	0.197
2.000	AM-50-51	556.250	3.070	3.050	-0.020	D2AM19	3.437	0.056	-0.692	-0.104	0.002	0.175
2.000	JM-82-83	734.250	3.810	3.840	0.030	D2JM13	3.753	0.121	-1.095	0.000	0.101	0.183
2.000	NB-35-36	756.500	3.680	3.660	-0.020	D4NB4	4.375	0.112	-1.305	0.000	0.638	0.208
2.000	NB-94-95	756.500	3.680	3.660	-0.020	D3NB9	4.399	0.089	-1.406	0.000	0.665	0.210
2.000	NB-43-44	756.500	3.660	3.630	-0.030	D1NB5	4.256	0.067	-1.285	0.000	0.534	0.214
2.000	KF-66-70	658.600	3.380	3.380	0.000	D4KF4	3.637	0.188	-0.894	0.000	0.501	0.191
2.000	AM-25-26	556.250	3.120	3.100	-0.020	D1AM3	4.086	0.068	-1.053	-0.025	0.237	0.180
2.000	AM-37-38	556.250	3.120	3.120	0.000	D2AM17	4.174	0.047	-1.104	-0.050	0.205	0.184
2.000	JB-52-53	765.400	3.810	3.780	-0.030	D2JB16	4.050	0.135	-1.065	0.000	0.551	0.021
2.000	BL-87-88	823.250	3.730	3.760	0.030	D4BL2	3.909	0.188	-1.048	0.000	0.343	0.212
2.000	KF-187-188	658.60	3.28	3.28	0.00	D2KF13	3.69	0.14	-0.82	0.00	0.44	0.188
2.000	JB-56-57	765.40	3.76	3.76	0.00	D4JB9	4.08	0.16	-1.03	0.00	0.64	0.201
2.000	jm-55-56	734.25	3.84	3.86	0.02	D1JM10	3.46	0.15	-0.68	0.00	0.25	0.191
2.000	jm-19-20	734.25	3.63	3.61	-0.02	D1JM5	3.76	0.15	-0.93	0.00	0.21	0.190
2.000	jm-47-48	734.25	3.68	3.66	-0.02	D1JM9	3.89	0.13	-0.84	0.00	0.37	0.190
2.000	NB-84-85	756.50	3.66	3.63	-0.03	D2NB11	4.43	0.09	-1.36	0.00	0.63	0.203
2.000	KF-226-227	658.60	3.33	3.33	0.00	D2KF17	3.49	0.20	-0.78	0.00	0.38	0.188

Table C2. *Force Data for "On" Pole Vaults (continued)*

Group	Name	BW (N)	Onstep	Takeoff	Difference	Force#	Verticalfz	AnteriorfyP	PosteriorfyB	MedialfxL	Lateralfxr	Tcontact
2.000	AM-31-32	556.25	3.18	3.20	0.02	D1AM4	4.16	0.10	-0.98	-0.04	0.19	0.186
2.000	AM-60-61	556.25	3.15	3.15	0.00	D2AM20	4.12	0.10	-1.02	-0.02	0.22	0.180
2.000	JB-33-34	765.40	3.78	3.73	-0.05	D1JB4	3.96	0.18	-0.93	0.00	0.56	0.192
2.000	JB-2-3	765.40	3.81	3.81	0.00	D3JB1	3.75	0.14	-1.09	0.00	0.40	0.202
2.000	JB-70-71	765.40	3.91	3.63	-0.28	D2JB20	3.68	0.21	-0.91	0.00	0.40	0.187
2.000	BL-23-24	823.25	3.63	3.63	0.00	D4BL15	4.16	0.15	-1.14	-0.05	0.23	0.205
2.000	BL-31-32	823.25	3.66	3.66	0.00	D4BL6	3.89	0.16	-1.04	0.00	0.24	0.207
2.000	BL-38-39	823.25	3.66	3.66	0.00	D4BL7	4.07	0.15	-1.21	-0.05	0.20	0.210
2.000	WL-77-78	867.75	3.63	3.61	-0.02	D3WL10	3.28	0.19	-0.79	-0.01	0.25	0.200
2.000	JM-9-10	734.25	3.71	3.71	0.00	D1JM4	4.08	0.07	-1.04	0.00	0.40	0.193
2.000	WL-73-74	867.75	3.63	3.66	0.03	D3WL9	3.01	0.19	-0.73	0.00	0.18	0.197
2.000	JB-75-76	765.40	3.78	3.78	0.00	D3JB10	3.86	0.18	-0.97	0.00	0.57	0.200
2.000	JB-35-36	765.40	3.78	3.78	0.00	D3JB6	3.96	0.16	-0.97	0.00	0.58	0.192
2.000	JB-66-67	765.40	3.78	3.78	0.00	D2JB18	4.00	0.17	-1.08	0.00	0.52	0.197
2.000	JM-120-121	734.25	3.78	3.78	0.00	D2JM19	4.08	0.11	-1.01	-0.02	0.19	0.195

Table C3. *Force Data for "Under" Pole Vaults*

Group	Name	BW (N)	Onstep	Takeoff	Difference	Force#	Verticalfz	AnteriorfyP	PosteriorfyB	MedialfxL	Lateralfxr
3.000	JM-44-45	734.250	3.810	3.400	-0.410	D4JM7	3.943	0.086	-0.861	-0.003	0.313
3.000	JM-5-6	734.250	3.810	3.660	-0.150	D1JM3	3.936	0.102	-0.847	0.000	0.384
3.000	JM-112-1	734.250	3.780	3.730	-0.050	D2JM17	3.824	0.083	-0.733	0.000	0.252
3.000	KF-66-69	658.600	3.350	3.230	-0.120	D4KF3	3.670	0.138	-0.867	0.000	0.510
3.000	KF-197-1	658.600	3.280	3.180	-0.100	D2KF14	3.336	0.161	-0.750	0.000	0.311
3.000	KF-220-2	658.600	3.300	3.070	-0.230	D2KF16	3.474	0.120	-0.796	-0.011	0.296
3.000	NB-108-1	756.500	3.680	3.450	-0.230	D2NB14	4.115	0.044	-1.247	0.000	0.488
3.000	NB-114-1	756.500	3.680	3.450	-0.230	D2NB15	4.328	0.030	-1.413	0.000	0.578
3.000	NB-140-1	756.500	3.680	3.510	-0.170	D2NB20	4.152	0.112	-1.174	0.000	0.605
3.000	JB-64-65	765.400	3.810	3.580	-0.230	D3JB9	3.508	0.179	-0.896	-0.031	0.204
3.000	AM-51-52	556.250	3.280	3.150	-0.130	D4AM25	2.927	0.115	-1.010	-0.076	0.173
3.000	NB-50-51	658.600	3.710	3.630	-0.080	D4NB6	5.137	0.091	-1.488	0.000	0.787
3.000	KF-51-52	658.340	3.380	3.120	-0.260	D1KF3	3.345	0.111	-0.861	0.000	0.457
3.000	JB-74-75	765.400	3.810	3.710	-0.100	D1JB10	4.091	0.161	-1.092	0.000	0.517
3.000	JB-26-27	765.400	3.810	3.630	-0.180	D3JB5	3.974	0.184	-0.950	0.000	0.555
3.000	JB-54-55	765.400	3.810	3.660	-0.150	D3JB8	4.048	0.152	-1.041	0.000	0.572
3.000	BL-7-8	823.250	3.710	3.660	-0.050	D4BL3	4.057	0.121	-1.167	0.000	0.349
3.000	BL-54-55	823.250	3.780	3.630	-0.150	D4BL9	4.051	0.146	-1.103	-0.021	0.202
3.000	BL-25-26	823.250	3.760	3.560	-0.200	D1BL2	3.769	0.142	-1.115	-0.087	0.169
3.000	BL-57-58	823.250	3.780	3.450	-0.330	D1BL5	3.729	0.100	-1.195	-0.136	0.124
3.000	JB-70-71	765.40	3.81	3.68	-0.13	D1JB9	4.28	0.16	-1.12	0.00	0.59
3.000	BL-17-18	823.25	3.71	3.45	-0.25	D1BL1	3.77	0.12	-1.23	-0.10	0.12
3.000	JM-71-72	734.25	3.58	3.51	-0.07	D3JM4	4.02	0.09	-0.85	0.00	0.41
3.000	NB-62-63	756.50	3.73	3.61	-0.12	D1NB7	4.27	0.12	-1.43	0.00	0.55
3.000	NB-7-8	756.50	3.61	3.53	-0.08	D1NB1	4.16	0.09	-1.31	0.00	0.56
3.000	NB-23-24	756.50	3.73	3.53	-0.20	D1NB5	4.26	0.07	-1.28	0.00	0.53
3.000	NB-53-54	756.50	3.71	3.63	-0.08	D1NB6	4.22	0.08	-1.39	0.00	0.53

Table C3. *Force Data for "Under" Pole Vaults (continued)*

Group	Name	BW (N)	Onstep	Takeoff	Difference	Force#	Verticalfz	AnteriorfyP	PosteriorfyB	MedialfxL	Lateralfxr
3.000	NB-62-63-2	756.50	3.68	3.58	-0.10	D4NB8	4.43	0.10	-1.37	0.00	0.62
3.000	NB-89-90	756.50	3.63	3.45	-0.18	D3NB8	4.59	0.07	-1.46	0.00	0.47
3.000	NB-40-41	756.50	3.63	3.51	-0.12	D3NB3	4.25	0.12	-1.28	0.00	0.52
3.000	KF-23-24	979.00	3.61	3.53	-0.08	D1KF1	2.46	0.07	-0.69	0.00	0.27
3.000	JB-65-66	765.40	3.84	3.73	-0.11	D4JB10	4.03	0.14	-0.92	0.00	0.48
3.000	JB-66-67	765.40	3.78	3.71	-0.07	D2JB18	4.00	0.17	-1.08	0.00	0.52
3.000	JB-7-8	765.40	3.81	3.71	-0.10	D1JB1	4.13	0.14	-1.13	0.00	0.68
3.000	JM-41-42	734.25	3.81	3.71	-0.10	D1JM8	4.01	0.09	-0.92	0.00	0.23
3.000	JB-48-49	765.40	3.81	3.61	-0.20	D4JB8	4.11	0.10	-1.26	0.00	0.51
3.000	JB-15-16	765.40	3.78	3.66	-0.12	D1JB2	3.97	0.16	-0.98	0.00	0.50
3.000	BL-79-80	823.25	3.76	3.53	-0.23	D3BL8	3.81	0.12	-1.12	-0.05	0.18
3.000	BL-14-15	823.25	3.76	3.40	-0.36	D3BL1	3.82	0.17	-0.99	0.00	0.26
3.000	BL-148-149	823.25	3.78	3.51	-0.27	D2BL11	3.65	0.16	-0.99	0.00	0.29
3.000	BL-181-182	823.25	3.78	3.38	-0.40	D2BL17	4.14	0.10	-1.19	0.00	0.28
3.000	BL-191-192	823.25	3.78	3.51	-0.27	D2BL18	3.66	0.13	-1.07	-0.06	0.14

APPENDIX D. RAW TIME DATA

Table D1. *Time Data for "Out" Pole Vaults*

Group	Name	BW (N)	Onstep	Takeoff	Difference	Force#	Tcontact	Tbreaking	Tpropulsive
1.000	JM-29-30	734.250	3.760	3.840	0.080	D4JM5	0.187	0.119	0.065
1.000	JM-52-53	734.250	3.630	3.810	0.180	D4JM8	0.188	0.123	0.063
1.000	JM-62-63	734.250	3.680	3.760	0.080	D3JM3	0.185	0.120	0.058
1.000	NB-69-70	756.500	3.660	3.710	0.050	D3NB6	0.210	0.145	0.062
1.000	NB-9-10	756.500	3.680	3.760	0.080	D4NB1	0.208	0.142	0.063
1.000	NB-74-75	756.500	3.680	3.730	0.050	D1NB9	0.208	0.151	0.050
1.000	KF-71-72	658.600	3.630	3.710	0.080	D4KF5	0.187	0.125	0.060
1.000	KF-157-1	658.600	3.250	3.380	0.130	D2KF11	0.187	0.122	0.062
1.000	KF-212-2	658.600	3.230	3.280	0.050	D2KF15	0.191	0.121	0.055
1.000	JB-43-44	765.400	3.810	3.910	0.100	D2JB15	0.187	0.122	0.062
1.000	AM-3-4	556.250	3.120	3.250	0.130	D2AM12	0.110	0.093	0.015
1.000	JM-52-53	734.250	3.630	3.840	0.210	D3JM2	0.191	0.125	0.057
1.000	JM-3-4	734.250	3.660	3.840	0.180	D1JM2	0.180	0.115	0.060
1.000	JM-78-79	734.250	3.730	3.810	0.080	D2JM12	0.191	0.128	0.050
1.000	JM-84-85	734.250	3.660	3.710	0.050	D3JM5	0.192	0.128	0.059
1.000	AM-5	556.250	3.120	3.250	0.130	D2AM13	0.180	0.120	0.058
1.000	AM-8-9	556.250	3.120	3.180	0.060	D2AM14	0.188	0.131	0.045
1.000	WL-185-1	867.750	3.610	3.810	0.200	D2WL3	0.193	0.123	0.065
1.000	WL-203-2	867.750	3.610	3.680	0.070	D2WL5	0.200	0.125	0.070
1.000	WL-228-2	867.750	3.580	3.780	0.200	D2WL8	0.190	0.122	0.060
1.000	WL-11-12	867.75	3.53	3.71	0.18	D3WL6	0.205	0.135	0.068
1.000	WL-216-217	867.75	3.56	3.78	0.23	D2WL6	0.198	0.125	0.06
1.000	WL-38-39	867.75	3.58	3.68	0.10	D3WL6	0.205	0.135	0.068

Table D2. *Time Data for "On" Pole Vaults*

Group	Name	BW (N)	Onstep	Takeoff	Difference	Force#	Tcontact	Tbreaking	Tpropulsive
2.000	JM-13-14	734.250	3.810	3.810	0.000	D1JM5	0.190	0.125	0.062
2.000	JM-42-43	734.250	3.730	3.760	0.030	D3JM1	0.186	0.128	0.055
2.000	JM-88-89	734.250	3.810	3.780	-0.030	D2JM14	0.193	0.125	0.066
2.000	NB-33-34	756.500	3.630	3.610	-0.020	D1NB4	0.214	0.157	0.054
2.000	NB-91-92	756.500	3.630	3.610	-0.020	D2NB12	0.210	0.149	0.058
2.000	NB-82-83	756.500	3.630	3.610	-0.020	D3NB7	0.213	0.150	0.061
2.000	KF-66-68	658.600	3.380	3.350	-0.030	D4KF2	0.190	0.123	0.065
2.000	KF-37-38	658.600	3.280	3.300	0.020	D1KF2	0.197	0.135	0.060
2.000	KF-59-60	658.600	3.280	3.300	0.020	D1KF4	0.191	0.123	0.066
2.000	JB-68-69	765.400	3.780	3.760	-0.020	D2JB19	0.197	0.132	0.060
2.000	AM-50-51	556.250	3.070	3.050	-0.020	D2AM19	0.175	0.120	0.053
2.000	JM-82-83	734.250	3.810	3.840	0.030	D2JM13	0.183	0.125	0.056
2.000	NB-35-36	756.500	3.680	3.660	-0.020	D4NB4	0.208	0.148	0.057
2.000	NB-94-95	756.500	3.680	3.660	-0.020	D3NB9	0.210	0.147	0.060
2.000	NB-43-44	756.500	3.660	3.630	-0.030	D1NB5	0.214	0.152	0.057
2.000	KF-66-70	658.600	3.380	3.380	0.000	D4KF4	0.191	0.125	0.060
2.000	AM-25-26	556.250	3.120	3.100	-0.020	D1AM3	0.180	0.130	0.047
2.000	AM-37-38	556.250	3.120	3.120	0.000	D2AM17	0.184	0.132	0.027
2.000	JB-52-53	765.400	3.810	3.780	-0.030	D2JB16	0.021	0.136	0.063
2.000	BL-87-88	823.250	3.730	3.760	0.030	D4BL2	0.212	0.140	0.070
2.000	KF-187-188	658.60	3.28	3.28	0.00	D2KF13	0.188	0.125	0.052
2.000	JB-56-57	765.40	3.76	3.76	0.00	D4JB9	0.201	0.133	0.066
2.000	jm-55-56	734.25	3.84	3.86	0.02	D1JM10	0.191	0.121	0.063
2.000	jm-19-20	734.25	3.63	3.61	-0.02	D1JM5	0.190	0.125	0.062
2.000	jm-47-48	734.25	3.68	3.66	-0.02	D1JM9	0.190	0.125	0.062
2.000	NB-84-85	756.50	3.66	3.63	-0.03	D2NB11	0.203	0.151	0.035

Table D2. *Time Data for "On" Pole Vaults (continued)*

Group	Name	BW (N)	Onstep	Takeoff	Difference	Force#	Tcontact	Tbreaking	Tpropulsive
2.000	KF-226-227	658.60	3.33	3.33	0.00	D2KF17	0.188	0.123	0.058
2.000	AM-31-32	556.25	3.18	3.20	0.02	D1AM4	0.186	0.128	0.042
2.000	AM-60-61	556.25	3.15	3.15	0.00	D2AM20	0.180	0.125	0.053
2.000	JB-33-34	765.40	3.78	3.73	-0.05	D1JB4	0.192	0.125	0.063
2.000	JB-2-3	765.40	3.81	3.81	0.00	D3JB1	0.202	0.137	0.063
2.000	JB-70-71	765.40	3.91	3.63	-0.28	D2JB20	0.187	0.120	0.065
2.000	BL-23-24	823.25	3.63	3.63	0.00	D4BL15	0.205	0.140	0.060
2.000	BL-31-32	823.25	3.66	3.66	0.00	D4BL6	0.207	0.139	0.065
2.000	BL-38-39	823.25	3.66	3.66	0.00	D4BL7	0.210	0.145	0.063
2.000	WL-77-78	867.75	3.63	3.61	-0.02	D3WL10	0.200	0.130	0.067
2.000	JM-9-10	734.25	3.71	3.71	0.00	D1JM4	0.193	0.137	0.045
2.000	WL-73-74	867.75	3.63	3.66	0.03	D3WL9	0.197	0.127	0.067
2.000	JB-75-76	765.40	3.78	3.78	0.00	D3JB10	0.200	0.132	0.066
2.000	JB-35-36	765.40	3.78	3.78	0.00	D3JB6	0.192	0.127	0.063
2.000	JB-66-67	765.40	3.78	3.78	0.00	D2JB18	0.197	0.130	0.065
2.000	JM-120-121	734.25	3.78	3.78	0.00	D2JM19	0.195	0.130	0.062

Table D3. *Time Data for "Under" Pole Vaults*

Group	Name	BW (N)	Onstep	Takeoff	Difference	Force#	Tcontact	Tbreaking	Tpropulsive
3.000	JM-44-45	734.250	3.810	3.400	-0.410	D4JM7	0.185	0.128	0.045
3.000	JM-5-6	734.250	3.810	3.660	-0.150	D1JM3	0.192	0.126	0.060
3.000	JM-112-1	734.250	3.780	3.730	-0.050	D2JM17	0.185	0.125	0.058
3.000	KF-66-69	658.600	3.350	3.230	-0.120	D4KF3	0.185	0.128	0.050
3.000	KF-197-1	658.600	3.280	3.180	-0.100	D2KF14	0.185	0.122	0.055
3.000	KF-220-2	658.600	3.300	3.070	-0.230	D2KF16	0.186	0.125	0.043
3.000	NB-108-1	756.500	3.680	3.450	-0.230	D2NB14	0.207	0.152	0.024
3.000	NB-114-1	756.500	3.680	3.450	-0.230	D2NB15	0.210	0.158	0.025
3.000	NB-140-1	756.500	3.680	3.510	-0.170	D2NB20	0.200	0.142	0.055
3.000	JB-64-65	765.400	3.810	3.580	-0.230	D3JB9	0.200	0.130	0.068
3.000	AM-51-52	556.250	3.280	3.150	-0.130	D4AM25	0.113	0.091	0.020
3.000	NB-50-51	658.600	3.710	3.630	-0.080	D4NB6	0.205	0.148	0.040
3.000	KF-51-52	658.340	3.380	3.120	-0.260	D1KF3	0.195	0.132	0.057
3.000	JB-74-75	765.400	3.810	3.710	-0.100	D1JB10	0.190	0.127	0.055
3.000	JB-26-27	765.400	3.810	3.630	-0.180	D3JB5	0.194	0.130	0.062
3.000	JB-54-55	765.400	3.810	3.660	-0.150	D3JB8	0.198	0.133	0.053
3.000	BL-7-8	823.250	3.710	3.660	-0.050	D4BL3	0.205	0.144	0.050
3.000	BL-54-55	823.250	3.780	3.630	-0.150	D4BL9	0.207	0.139	0.065
3.000	BL-25-26	823.250	3.760	3.560	-0.200	D1BL2	0.207	0.145	0.060
3.000	BL-57-58	823.250	3.780	3.450	-0.330	D1BL5	0.210	0.145	0.062
3.000	JB-70-71	765.40	3.81	3.68	-0.13	D1JB9	0.194	0.132	0.06
3.000	BL-17-18	823.25	3.71	3.45	-0.25	D1BL1	0.21	0.153	0.054
3.000	JM-71-72	734.25	3.58	3.51	-0.07	D3JM4	0.189	0.130	0.057
3.000	NB-62-63	756.50	3.73	3.61	-0.12	D1NB7	0.210	0.157	0.054
3.000	NB-7-8	756.50	3.61	3.53	-0.08	D1NB1	0.210	0.153	0.050
3.000	NB-23-24	756.50	3.73	3.53	-0.20	D1NB5	0.214	0.151	0.057

Table D3. *Time Data for "Under" Pole Vaults (continued)*

Group	Name	BW (N)	Onstep	Takeoff	Difference	Force#	Tcontact	Tbreaking	Tpropulsive
3.000	NB-53-54	756.50	3.71	3.63	-0.08	D1NB6	0.213	0.155	0.056
3.000	NB-62-63-2	756.50	3.68	3.58	-0.10	D4NB8	0.215	0.154	0.053
3.000	NB-89-90	756.50	3.63	3.45	-0.18	D3NB8	0.208	0.155	0.050
3.000	NB-40-41	756.50	3.63	3.51	-0.12	D3NB3	0.205	0.147	0.055
3.000	KF-23-24	979.00	3.61	3.53	-0.08	D1KF1	0.198	0.138	0.048
3.000	JB-65-66	765.40	3.84	3.73	-0.11	D4JB10	0.193	0.127	0.052
3.000	JB-66-67	765.40	3.78	3.71	-0.07	D2JB18	0.197	0.130	0.065
3.000	JB-7-8	765.40	3.81	3.71	-0.10	D1JB1	0.198	0.135	0.053
3.000	JM-41-42	734.25	3.81	3.71	-0.10	D1JM8	0.190	0.128	0.058
3.000	JB-48-49	765.40	3.81	3.61	-0.20	D4JB8	0.198	0.135	0.057
3.000	JB-15-16	765.40	3.78	3.66	-0.12	D1JB2	0.195	0.128	0.057
3.000	BL-79-80	823.25	3.76	3.53	-0.23	D3BL8	0.203	0.143	0.045
3.000	BL-14-15	823.25	3.76	3.40	-0.36	D3BL1	0.210	0.140	0.064
3.000	BL-148-149	823.25	3.78	3.51	-0.27	D2BL11	0.210	0.142	0.065
3.000	BL-181-182	823.25	3.78	3.38	-0.40	D2BL17	0.200	0.145	0.052
3.000	BL-191-192	823.25	3.78	3.51	-0.27	D2BL18	0.210	0.145	0.062