THE UNIVERSITY OF MANITOBA

A BIOMECHANICAL COMPARISON OF THE INDOOR AND OUTDOOR VOLLEYBALL SPIKE APPROACH AND TAKE-OFF

By:

Adrian Honish

A Thesis Study
Submitted to the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

Faculty of Physical Education and Recreation Studies
June, 2005

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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A Biomechanical Comparison of the Indoor and Outdoor Volleyball Spike Approach and Take-Off

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ACKNOWLEDGEMENTS

I would like to thank all of my committee members: Dr. Marion Alexander, Dr. Janis Butcher, and Dr. Lorne Sawula for their time, support and input that went towards the completion of this study. Special thanks go to Dr. Marion Alexander for the irreplaceable practical experience and learning opportunities that she provided throughout my years in the faculty of graduate studies. Her support and encouragement were a huge help and driving force towards completing this study.

I would like to extend my thanks to all the subjects who gave their time and energy to participate in this study and be a part of sports science and the development of the sport of beach volleyball. I would also like to thank all the coaches and sport organizations that accommodated to the collection of data. This includes Volleyball Canada, Lorne Sawula, Ken Bentley and Marie-Christine Rousseau.

To my fellow students in the biomechanics lab including Dana Way and Carolyn Taylor, thank you for your insight and assistance with this study and for all your support and patience dealing with the good times and the tough times. I would like to extend this thanks to Jeff Leiter for leading the way; you're a tough act to follow. A special thanks to Dana Way and Sean Mulvey for all their help with data collection and for making the 30 hour road trip with me to the harsh land of Wasaga Beach to collect the outdoor group data. Mulvey, you're the best ball shagger I could have had. Thank you Dana for sharing this experience with me. We hung in there and got through everything together.

Most importantly I would like to thank my family: Mom, Dad, and Kyle, thank you for all of your support over several years of school and for being there whenever I needed you.

A special thanks to my fiancée Cheryl for going through this with me and for your never ending understanding and support. I don't know how you put up with my ridiculous schedule and I can't express how much I appreciated it. You gave me a reason to finally go home some nights.

DEDICATION

I would like to dedicate this study and the work that went into it to the memory of Dad who passed away with cancer two days after I returned from my data collection. Thank you dad for giving me the strength and will to complete this study through tough times and for your constant support throughout my life, including my last 21 years of schooling. The hard work that went into this study and the future things to come are a true example of the time, attention and constant effort that you put into me over the years. This study is largely thanks to you. Thank you.

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ABSTRACT

The purpose of this study was to determine the kinematic differences between the beach volleyball and indoor volleyball spike approaches and take-off by identifying those factors responsible for the decrease in jump height in the outdoor spike approach. Ten indoor and ten outdoor elite female volleyball players were videotaped (60 Hz) performing the volleyball spike approach and take-off and 23 independent variables were compared between subjects. Three-dimensional coordinates were generated using direct linear translation calculations and used for kinematic analysis of the approach and take-off for the respective groups. Vertical displacement of the center of mass from its position at take-off to peak height was used as a measure for vertical jump performance. The outdoor subject group showed significantly lower vertical jump heights than the indoor subjects by a mean difference of 5.8cm ($p<.05$). Several additional differences between variables measured were found to be significant between groups with the main differences occurring during the plant phase of the spike approach. Correlations and a stepwise regression analysis were also performed on the data set for each of the indoor and outdoor subject groups in order to determine the variables that best predict jump height. For both subject conditions step-close time was found to be the best predictor of jump height explaining 65% and 27% of variance in the indoor and outdoor subject groups respectively. Stepwise regression analysis of the indoor spike approach selected a total of eight variables as the key predictors of jump height, five of which occur during the plant phase further explaining the importance of the plant phase and the importance of the differing results seen in the variables measured during the plant phase of the outdoor subject group.

“A BIOMECHANICAL COMPARISON OF THE INDOOR AND OUTDOOR VOLLEYBALL SPIKE APPROACH AND TAKE-OFF”

CHAPTER 1

INTRODUCTION

The game of volleyball has been played for over a century. Invented by William G. Morgan in 1895, it recently celebrated its 100 year anniversary. William G. Morgan, an instructor at the Young Men's Christian Association (YMCA) in Holyoke, Massachusetts, decided to blend elements of basketball, baseball, tennis, and handball to create a game for his classes of businessmen which would demand less physical contact than basketball. He created the game of Volleyball (at that time called mintonette). Morgan borrowed the net from tennis, and raised it 6 feet 6 inches above the floor, just above the average man's head. During a demonstration game, someone remarked to Morgan that the players seemed to be volleying the ball back and forth over the net, and perhaps "volleyball" would be a more descriptive name for the sport (Reeser & Bahr, 2003).

The first game was played at Springfield College, Massachusetts in 1896 (Reeser & Bahr, 2003). It then spread around the world as the YMCA continued to expand first to Canada, the orient and the Southern Hemisphere in 1900, and later to the rest of the world. Over the years the game has grown immensely through the development of its rules, strategy and the athletes who participate in the sport. It was 1916 when the sport of volleyball experienced a pinnacle of development in how the game would be played for years to come. In the Philippines, an offensive style of passing the ball in a high trajectory to be struck by another player was introduced. The attack was termed the "Filipino Bomb" and today is referred to as the spike. The Filipinos also developed the "bomba" or kill (an attack resulting in an immediate point), and called the hitter a "bomberino". In 1920, as a possible result of this new technique, the net was raised to 8 feet and remains there to this date.

The Federation Internationale de Volley-Ball (FIVB) was founded in Paris in 1947 and remains the governing body for volleyball internationally. The first world championships were held in 1949 in Prague, Czechoslovakia and in 1957 the International Olympic Committee (IOC) designated volleyball as an Olympic team sport to be included in the 1964 Olympic Games in Tokyo (Resser & Bahr, 2003).

Unlike its predecessor, the sport of beach volleyball has not been around long, but is in fact a relatively new sport growing at an accelerating rate among both competitors and spectators. Although William G. Morgan invented the sport of volleyball in 1895, it was not until 1930 that the first beach volleyball game was played on the beach in Santa Monica, California (History of beach volleyball 2005). Even then, it was only for fun and no organized league existed until the 1950's. In 1985, the FIVB instituted the first Men's Beach Volleyball World Championships in Ipanema, Brazil and in 1993 the Women's World Championship Series was initiated. However, it wasn't until beach volleyball's recent Olympic debut at the 1996 Atlanta Summer Games that it earned a more distinguished place in sport. With 24 men's teams and 18 women's teams representing 19 different countries and over 107,000 spectators over a 6-day period in a

10,000 seat stadium, the sport rose in popularity. With this comparatively young and high-energy game, and the increasing interest in it, there is a major need for research in the area.

While the technical skills of beach volleyball do not vary extensively from the indoor game, the sport remains unique in terms of the rules and strategy of the game. Competitive beach volleyball played at the international level is played with two-player teams and is referred to as doubles play as opposed to the traditional indoor game where six players on a team play at the same time. Although beach volleyball is often played with various numbers of players on a team from two to six, only doubles competition is played at the international level and will be the focus of this study. Another key difference between the indoor and outdoor game is the court size. Indoor volleyball is played on a nine meter by nine meter court on each side of the net. In order to increase the allure of beach volleyball by increasing the likelihood of longer rallies, the court size for beach volleyball doubles was decreased in 2002 to eight meters by eight meters on each side of the net. The most profound difference between the indoor and beach volleyball games is the surface on which they are played. The indoor game is most commonly played on a hardwood or polypropylene surface while the outdoor game is played on a soft sand surface of 40 cm in depth. This creates many difficulties in performing the necessary skills of volleyball proficiently as it will inevitably affect mobility and jumping. Some other small ball handling differences exist between the two games but are not important to be discussed here.

The volleyball spike is one of the most important and yet one of the most difficult techniques a volleyball player must master. The athlete is expected to determine the path of the ball, to approach, jump, and then hit the ball with maximum force at the peak height of his or her jump. All of this needs to be accomplished consistently, efficiently, and with the most precise timing to allow the athlete's hand to come into clean contact with the ball. The spike approach has been studied in regards to the indoor volleyball game; however, researchers have barely begun to examine the skills of the outdoor game. With the outdoor game played on a sand surface over 40 centimeters deep, the spike approach is much more difficult to perform and does not allow athletes to achieve the jump heights witnessed in the indoor game.

A study by Bishop (2003) from the University of Western Australia measured the vertical jump of 18 beach volleyball players on both wood and sand surfaces. All jump heights measured on sand were found to be significantly lower than those on the much harder wood surface. He suggests that uncompacted sand is close to the soft end of the surface-stiffness continuum and absorbs almost 100% of energy. Therefore, it is likely that the decrease in jump height on sand is due to a reduction in ground reaction forces and a longer contraction time.

Understanding the mechanics involved in attaining maximum height during the spike approach will be beneficial to both coaches and players. Familiarizing coaches with the mechanical differences between the indoor and outdoor spike approaches and providing ways to minimize decreases in jump performance evident in the outdoor game will help to better prepare athletes for their transition to the sand surface.

PURPOSE OF THE STUDY

The purpose of this study was to determine the kinematic differences between the outdoor (beach) volleyball and the indoor volleyball spike approach and take-off, by identifying those factors responsible for the decrease in jump height attained in the outdoor spike approach. A subpurpose was to draw coaching implications that will help to minimize the decrease in performance.

NULL HYPOTHESIS

The following null hypothesis was adopted for this study:

1) The biomechanics of the beach volleyball spike approach and take-off would not differ from the indoor spike approach and take-off (2) Peak vertical jump height would not be lower on the sand surface.

RATIONALE FOR THE STUDY

The sport of beach volleyball is relatively new in its development and the skills of the game have not been widely studied. With a rapidly growing interest in the sport following its entry into the summer Olympics in 1996, there is a need for critical analysis of the skills to further develop the game itself. The majority of athletes participating in the sport of beach volleyball began their volleyball career at an early age with the indoor game, before eventually making a transition to the outdoor sand court. As a result, the technical skills of indoor volleyball are learned early on and these movement patterns are well learned with countless repetitions over several years. This learning develops motor patterns and habits that are specific to indoor volleyball, but may not be ideal for the outdoor game. It is understandable for one to assume that competing on a sand surface 40 centimeters in depth, as compared to the standard wood surface of an indoor court, may dramatically alter an athlete's technique so long as he or she is in contact with the sand. Studies specific to the skills of beach volleyball will help to identify some of these differences that may exist between the indoor and outdoor game.

The skills most affected by the softer surface are likely the spike approach, plant, and take-off as the athlete is required to run three or four steps through the sand towards the net, plant the feet and forcefully jump as high as possible to spike the ball. The technique used for jumping in the sand is dramatically different from that used on hard courts. The sand is a much softer surface and absorbs a large amount of energy before a hitter reaches his take-off point (Wells, 1996). An experienced beach player knows through past experience that an indoor approach technique is somewhat ineffective in the sand. By conducting an analysis of the biomechanics of both the indoor and outdoor spike approaches, differences between the two can be clearly identified. Through identification of these differences, the transition from the indoor to outdoor game can be made more smoothly as awareness of the changes that must be made to the technique of the indoor spike approach will be available to both coaches and athletes.

LIMITATIONS

1) The selection of only highly skilled female subjects decreases the ability to generalize the results to male volleyball players.
2) The sample size is small (n = 10 per group) and is not sufficient to attain statistical power. It is questionable to conclude that differences between variables are solely the result of changes in court surface and not due to inter-subject differences.
3) There is very little available research on the outdoor spike approach to which comparisons can be made.

4) The athletes are filmed in a controlled setting as opposed to live competition. This may have some influence on the behavior of the subjects, decreasing the reliability of the research.

COACHING IMPLICATIONS

This study will familiarize coaches and athletes with the effects the sand surface has on the mechanics of the spike approach. The majority of athletes competing in the sport of beach volleyball have played years of indoor volleyball prior to their transition to the beach. For this reason, they often approach the outdoor game with the same technical skills that they use for the more familiar indoor game. Players realize that the two games are very different and adaptations need to be made in order to be successful. This study will describe those adaptations and give coaches and athletes the opportunity to better prepare for the transition and to further advance technically in the sport of beach volleyball.

DEFINITION OF TERMS

Acceleration: the rate at which the velocity changes with respect to time (Hay, 1993)

$a = (v_f - v_i)/t$: *where* a = the average acceleration; v_f = the final velocity; v_i, the initial velocity and t = time.

Angular acceleration (α): the rate of change in angular velocity (Hall, 2003).

$\alpha = (\omega_f - \omega_i)/t$: where α = angular acceleration; ω_f = final angular velocity; ω_I = initial angular velocity; and t = time.

Angular displacement (∅): change in angular position (Hall, 2003)

Angular momentum: quantity of angular motion possessed by a body that is equal to the product of moment of inertia and angular velocity; $H=mk^2\omega$, where m=mass, k=the radius of gyration, and ω=angular velocity (Hall, 2003).

Angular velocity: rate of change of angular position (Hall, 2003)

$\omega = \varnothing/t$: *where* ω = angular velocity; $\varnothing$ = angular displacement; and t = time

Axis of rotation: imaginary line perpendicular to the plane of rotation and passing through the center of rotation about which rotation occurs (Hall, 2003).

Center of Mass (center of gravity): point around which a body's weight and mass are equally balanced in all directions (Hall, 2003). The Peak 5 Motion Analysis system determines the position of the center of gravity in a body by taking into account the contribution of each individual segment to the total mass of the system and the position of the center of gravity of each individual segment (from tables determined by cadaver studies). The point about which the sum of all the individual torques due to the segments will equal zero is the center of gravity.

Impulse: the product of an applied force and the time over which the force is applied. Also equal to the change of momentum. (Hall, 2003). In jumping skills such as the volleyball spike approach, the athlete can produce greater impulse by applying muscle forces over a very short time (Hay, 1993). $I = Ft$, where F=force and t=time.

Momentum: the product of the mass of a body or object and the velocity at which the body or object is travelling (Hall, 2003). A volleyball spiker attempts to generate horizontal momentum during the approach and later use that to help produce vertical momentum at take-off.

Stretch-Shortening Cycle: Eccentric contraction followed immediately by concentric contraction utilizing energy stored in the series and parallel elastic components of muscle (Hall, 2003).

Work: The work done on a body by a force is equal to the product of its magnitude and the distance that the body moves in the direction of the force, while the force is being applied to it (Hay, 1993). W = Fd, where W = work; F = force; and d = distance over which the force is applied.

CHAPTER 2

REVIEW OF LITERATURE

Many researchers (Sampson & Roy, 1976; Coutts, 1978; Alexander & Seaborn, 1980; Maxwell, 1982; Van Ingen Schenau, Bobbert, Huijing, 1985; Wilkerson, 1985; Harman & Rosenstein, 1990; Coleman, Benham, Northcott, 1993) have investigated the technique of the indoor volleyball spike. However, due to the recent development of beach volleyball, there is very little research available specific to the mechanics of the outdoor spike. Currently, they are seen as almost the same skill. This is justified to the extent that they require very similar motor patterns and basic mechanics, yet alterations and adaptations need to be made in adjustment to the different playing conditions, especially the sand surface of the outdoor game. Therefore, due to little research available describing the outdoor game, the majority of this review of literature will focus mainly on the indoor volleyball spike.

Dowling and Vamos (1993) have defined the vertical jump as a measure of the vertical displacement of the center of mass from the instant of take-off to the peak of the jump. In other words, it is calculated by subtracting the height of the center of mass at take-off from the height of the center of mass at the peak of the jump. Vertical jump height is determined by several factors, which are controlled or manipulated throughout the phases of the spike described by Coleman et al. (1993). The volleyball spike can be broken down into the following six phases: the approach; the plant, which is defined as the ground contact prior to take-off; take-off; flight, which incorporates the movements of the body prior to contact; the hitting action; and landing and recovery (Coleman et al., 1993). For the scope of this study, the approach, plant, and take-off will be studied thoroughly, with some attention placed on the flight phase as an outcome of the first three phases.

Approach Phase

The approach phase usually begins about three meters from the net and involves the spiker taking two or three steps at an approximate 45 degree angle to the net. Coleman et al. (1993) describe how the player gradually lowers the center of mass in order to minimize the amount of work required to reduce the downward acceleration of the athlete during the absorption phase of foot plant. The athlete begins the approach with the center of gravity relatively high compared to its position at the end of the plant phase when the athlete is in a crouched position with optimal knee flexion. If the center

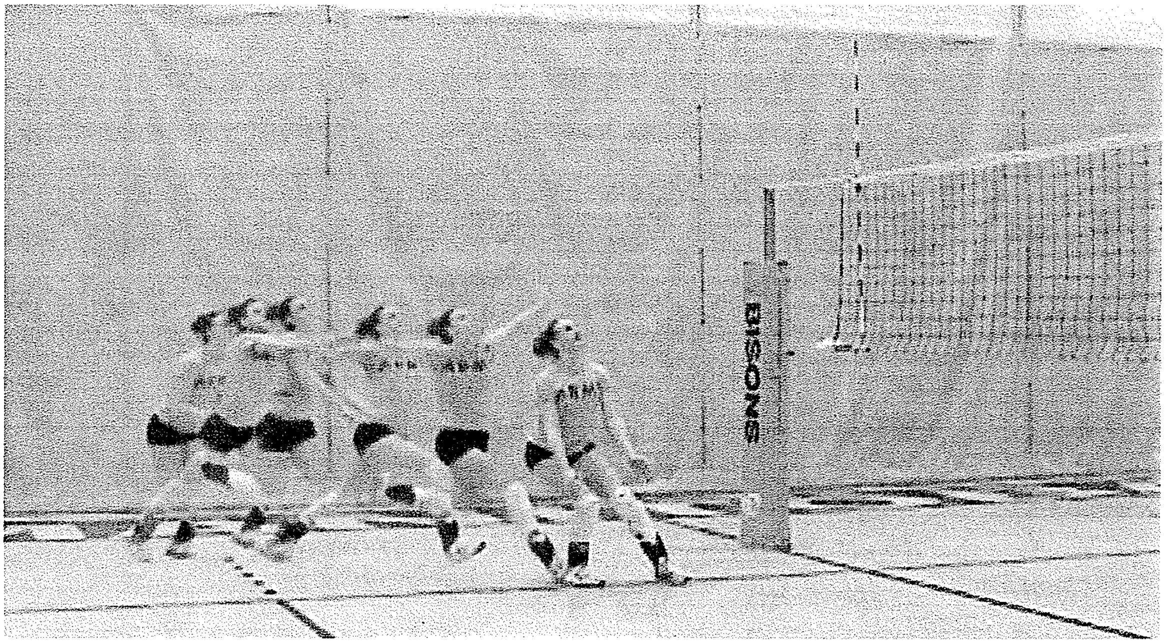


Figure 2.1: Approach phase of indoor spike approach

of mass is not lowered gradually, it will need to be lowered quickly as the feet are planted at the end of the approach phase. This technique would result in a much larger downward acceleration of the center of mass than if it were lowered gradually over the course of the entire approach. The athlete would then need to generate considerably more force as the knee and hip extensors contract eccentrically to reduce the downward acceleration resulting in a greater amount of negative work done (negative work = force x downward distance). This lowering of the center of mass is important to increase the distance over which force can later be applied prior to take-off. According to Sampson and Roy (1976), this continues over approximately 40% of the approach. Figure 2.1 illustrates the approach phase of the spike approach.

Another characteristic of the approach involves the use of the arms. As the first step occurs, the directional step to determine the athlete's path to intercept the ball, the arms are placed in a position of slight shoulder flexion in the direction that the athlete will approach (Figure 2.2). This forward motion of the arms moves the body's center of mass forward, and creates an equal and opposite reaction backwards increasing the force of knee and hip extension that drives the athlete forward and initiates the approach. The final stride of the approach is the longest step. It begins, for a right hand dominant athlete, by forcefully extending at the knee and hip joints of the left leg while plantar flexing

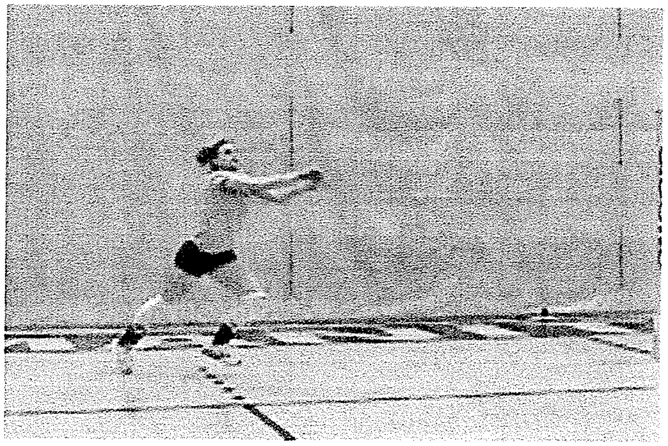


Figure 2.2: First step of approach phase. Shoulder flexion places arms in front of body to maintain balance

the ankle to propel the athlete forward (Figure 2.3). Simultaneously the right knee flexes slightly, decreasing the moment of inertia about the right hip joint by decreasing the perpendicular distance from the center of mass of the leg to the axis through the hip joint. This allows the right leg to be brought forward faster and with less resistance to prepare it for foot plant ahead of the athlete. Because of the characteristic airborne phase in the final step it is often considered a hop. This hop-step is necessarily long in order to generate large enough braking forces that will decrease the horizontal momentum of the athlete and limit the amount of forward motion that will occur after take-off. The final stride is shown in Figure 2.4. During the final stride, the arms are forcefully abducted and hyper-extended behind the athlete to a point where they are parallel to the ground or slightly above parallel. This

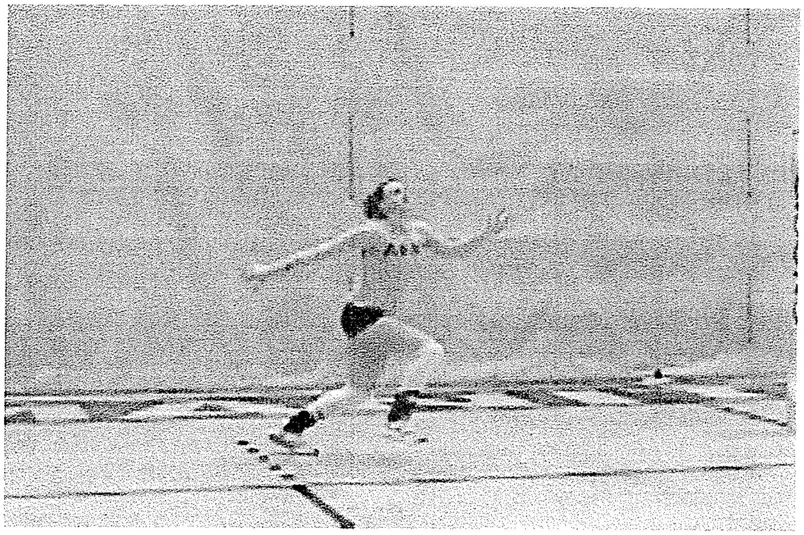


Figure 2.3: Extension of back leg initiating final step of spike approach

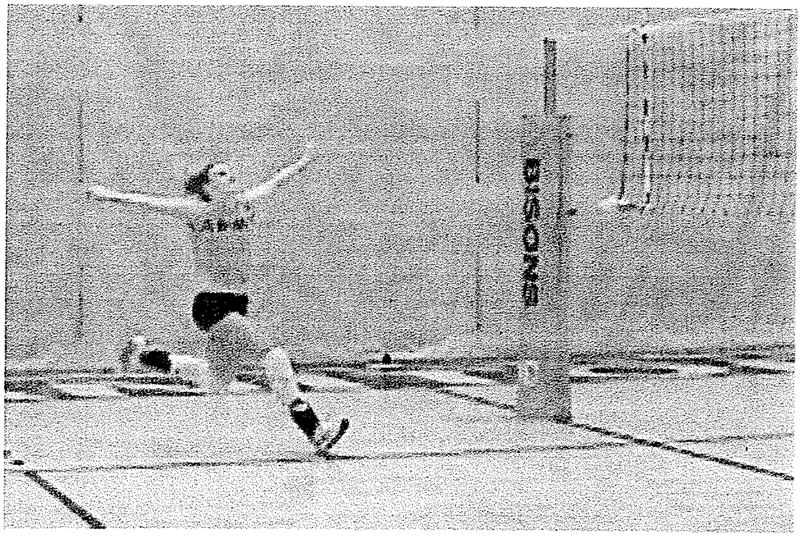


Figure 2.4: Final step of approach phase. Breaking force applied to ground to decrease horizontal momentum

hyperextension and abduction places the arms in an ideal position for the forceful arm swing to follow.

It is also important to generate sufficient horizontal momentum during the approach so that on the last stride, when the feet are planted for the jump and braking forces act back on the body, the horizontal force will cause flexion to occur at the knee and hip joints. This flexion in combination with increased stiffness in the joints will produce a powerful pre-stretch on the muscles crossing the knee and/or hip and will later be able to contract concentrically with more force to maximize vertical velocity at takeoff. Dapena (1988) states that a fast run-up in the sport of high jump allows the athlete to exert a larger vertical force on the ground. As the athlete plants the takeoff leg the horizontal velocity of the athlete forces the knee to flex, the quadriceps muscles (knee extensors) contract and try to resist flexion of the knee joint. The momentum of the athlete causes the quadriceps muscles to stretch during contraction (eccentric contraction), initiating the stretch reflex of the quadriceps muscle group. The stretch reflex initiates a powerful contraction in the extensor muscles of the knee producing large vertical forces on the ground. In turn, the ground exerts equal and opposite vertical forces (ground reaction force) on the athlete. The greater the vertical ground reaction force the higher the athlete will jump, since greater impulse will produce a greater change in velocity.

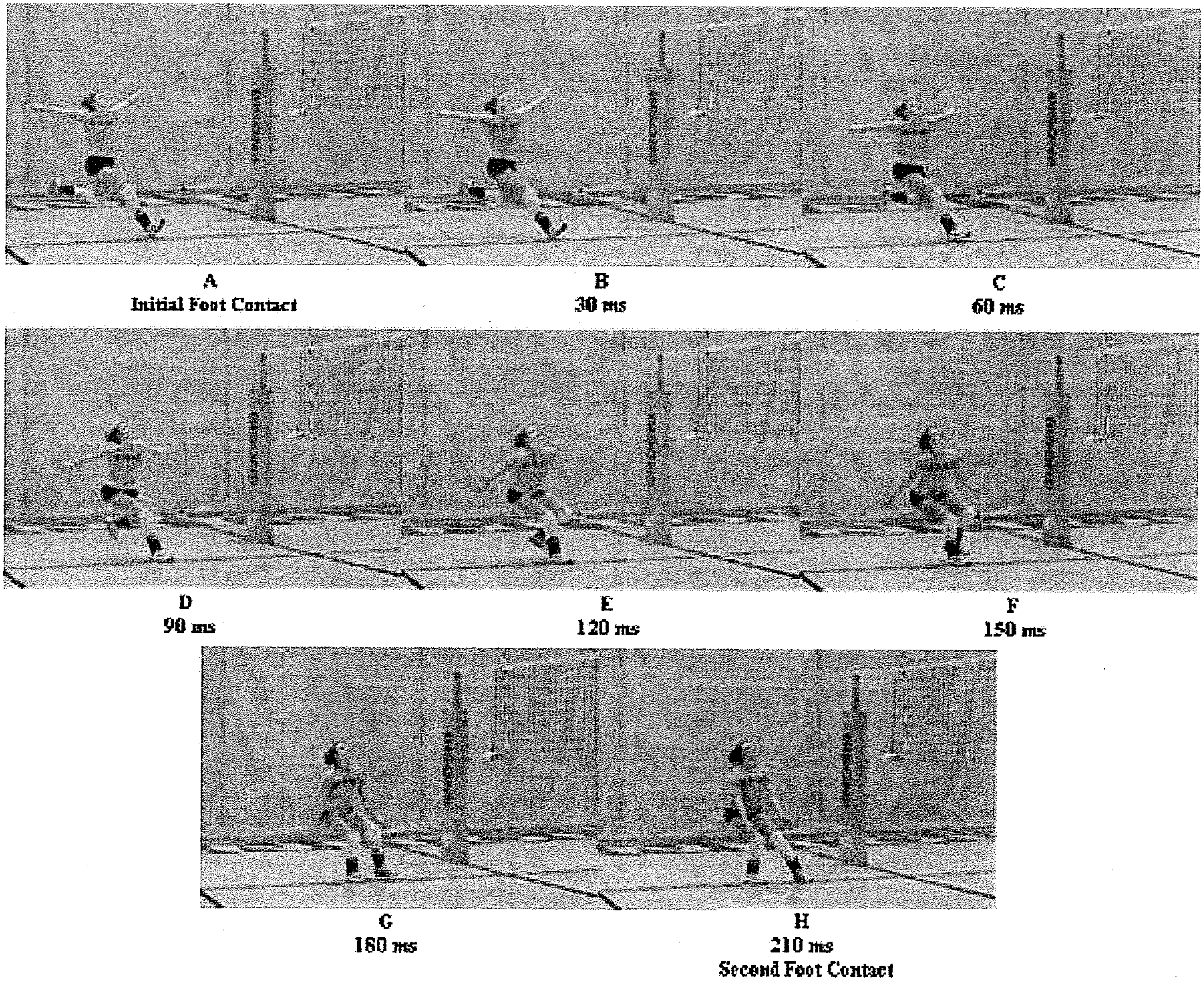
Plant Phase

In the plant phase, the trailing foot is brought forward to join the leading foot. The last step is usually either a long, low skip or a small jump (Coleman et al., 1993).

Coutts (1978) has defined these two styles as the 'step-close' and the 'hop' respectively. He further described two patterns of the step-close: the 'slow step-close' and the 'fast step-close'. Coutts' research has shown the primary difference between the three techniques to occur when the momentum of the approach is being absorbed by the muscles, tendons, and ligaments of the body (Coutts, 1978). The hop approach and foot plant is characterized by landing on both feet simultaneously prior to take-off and was shown to have the shortest absorption time with the highest peak force. This is because the vertical and horizontal momentum of the athlete is absorbed quickly and at the expense of a high amount of stress placed on the tissues of the body. In Coutts' study, subjects using the 'hop' technique demonstrated a peak absorption force of five times their body weight over a period of 0.27 seconds.

The slow step-close was characterized by more of a three-phase absorption pattern prior to the final main impulse. These three phases of absorption are clearly explained by Coutts (1978): "the player pumps the brakes slightly when the first foot contacts the floor in the last approach step, then pumps the brakes again when the second foot makes contact, and puts a final tap on the brakes before the main extension effort is initiated" (p 11). The slow step-close was therefore shown to be effective in spreading the absorption of momentum over a longer period of time, and thus reducing the peak forces on the lower body (momentum = mass x velocity). Data from Coutts' study showed this technique to generate a peak absorption force of only 2.8 times body weight over approximately 0.46 seconds.

The final spike approach style was the fast step-close technique. It is similar to the slow step-close technique in the sense that both feet do not contact the floor at the same time in preparation for take-off. However, the time delay between the plant of the first and second foot is so short that mechanically, it is similar to the hop approach. Both feet are planted almost simultaneously and therefore generate a fast braking action resulting in higher peak absorption forces than the slow-step close, but lower forces than


A
Initial Foot Contact

B
30 ms

C
60 ms

D
90 ms

E
120 ms

F
150 ms

G
180 ms

H
210 ms
Second Foot Contact

Figure 2.5: Fast step-close technique. Still photos taken at 30 ms intervals with total sequence lasting 210 ms (0.21 sec).

seen in the hop. Figure 2.5 illustrates a fast step-close technique where the right foot is planted initially and followed almost immediately by the trailing left foot. Each still photo (A to H) is taken 30 ms apart with the entire time delay between the initial foot contact and the end of the step-close equal to 210 ms (0.21 sec).

Coutts (1978) concluded his study by stating there was no evidence as to which technique would generate the higher vertical jump. However, the hop technique was able to get the player off the ground the quickest. Unfortunately, the high peak force necessary to attain that speed was much more likely to cause injury. The hop approach required the most strength in the muscles, tendons, and other force absorbing structures of the body, and is therefore not recommended for weaker players, or players recovering from injury.

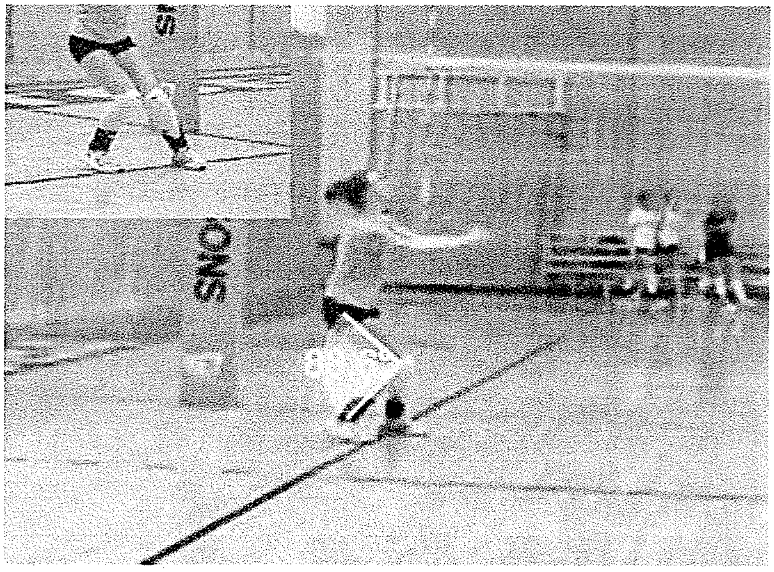


Figure 2.6: Knee flexed to 88.6-degrees from anatomical position. Close to suggested ideal of 90-degrees (Alexander & Seaborn, 1980)

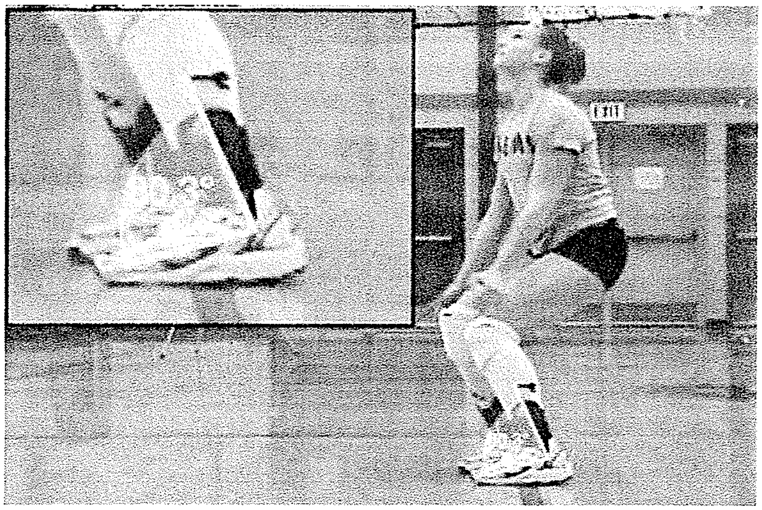


Figure 2.7: Ankle dorsi flexed 9.7 degrees from anatomical position (90-80.3 degrees). Nichols (1973) suggests optimal amount of dorsi flexion close to 10-degrees.

At the end of the plant stage (Figure 2.6), the hips and knees are flexed to ideally 90 degrees from the anatomical (Alexander & Seaborn, 1980). The trunk should also be flexed forward into a position where the shoulders are in line with or slightly in front of the knees. As well, Nicholls (1973) proposed that the optimal amount of dorsi flexion in the ankles should approach approximately ten degrees (Figure 2.7). A research study by researchers at the University of Amsterdam (Van Ingen Schenau et al., 1985) suggests that by placing muscle fibers on a stretch, large amounts of energy can be stored within the series and parallel elastic components of the muscle. They further suggest the possibility that much of the energy used for plantar flexion specifically could have been stored in the series elastic components of the soleus and gastrocnemius muscles and, given the possibility of power transport, in more proximally located muscles (Van Ingen Schenau et al., 1985). In order to utilize the energy storage properties of the series elastic component of muscle, longer stretching distances would need to be achieved. By attaining knee and hip angles close to ninety degrees of flexion, the athlete maximizes the use of a longer muscle moment arm while placing the knee and hip extensors on a stretch sufficient for energy storage in the series elastic component. This energy can be used to forcefully extend the two joints during the concentric contraction of the take-off phase.

The stretch-shortening cycle, as referred to by Chu (1998), suggests that the forceful stretch reflex of a muscle (concentric contraction activated by a pre-stretch of that same muscle) responds to the rate at which a muscle is stretched and is among the fastest in the human body. The faster the muscle is stretched or lengthened, the faster a contraction will occur, and the greater the concentric force output will be. The result of this is a more forceful movement overcoming the downward velocity of the spiker's body during the crouch and prior to take-off. This theory is also supported by past research on the kinetic and temporal factors related to vertical jump performance (Dowling & Vamos, 1993). It suggested that the ratio of negative to positive impulse was a major factor in determining jump height and that vertical jump performance was enhanced when athletes first performed negative work prior to positive work. Therefore, the greater the negative impulse, the greater the amount of negative work that must be performed prior to the positive work phase.

In order to maximize jump performance by fully utilizing the effects of the stretch-shortening cycle, research has shown that muscles of the lower extremities are activated before ground contact in order to stiffen the joints in preparation for touch down. This pre-activation is essential for energy potentiation and thus is an important element of a powerful push off (Reeser & Bahr, 2003). If during the eccentric loading phase at landing, the muscle-tendon complex is loaded up to its critical tension, forceful disruption of the actin-myosin cross-bridges may occur. This results in a loss of stored elastic energy within the eccentrically loaded muscle. Pre-activation of the muscle prior to impact increases the tension in the musculotendinous complex preventing excessive lengthening of the muscle and therefore in part preventing cross-bridges from breaking. This allows potential elastic energy generated by the eccentric loading phase to be preserved (Reeser & Bahr, 2003).

In conclusion in the plant phase of the volleyball spike, the line of gravity is situated behind the line of the heels (Figure 2.8). This is to brake the forward movement of the athlete and prevent the player from contacting the net or drifting too far forward. In addition, it also aids in the subsequent eccentric loading of hip and knee extensors in preparation for the jump. The further behind the knee joint the line of gravity lies, the longer the perpendicular distance from the line of gravity (resistance force) to the knee joint axis. This will result in a much greater amount of force that must be generated in the knee and hip extensors in order to overcome the torque caused by the weight of the upper body. Therefore, a larger eccentric contraction is elicited.

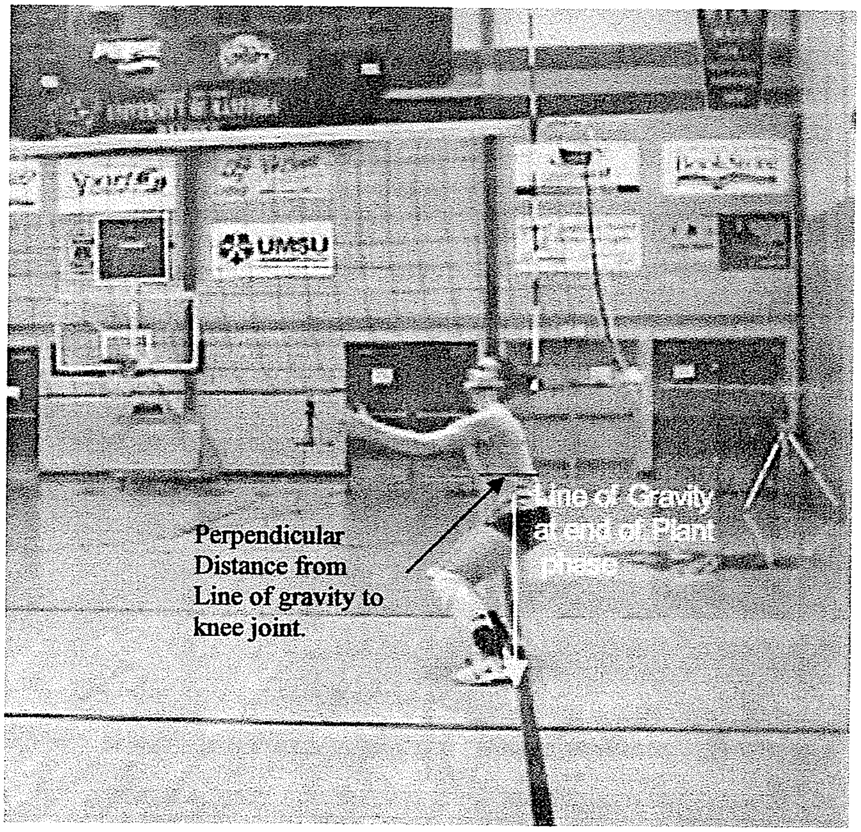


Figure 2.8: Braking force generated to reduce horizontal momentum and produce flexion at the knee and hip joints (eccentric contraction of knee and hip extensors initiates onset of stretch-shortening cycle.

Take-Off Phase

The take-off phase commences with the rapid extension of the trunk, hips, knees and ankles in conjunction with shoulder flexion. It is the force-producing phase of the spike approach with the main goal of maximizing the vertical velocity of the center of gravity at take-off. The phase begins with a rapid flexion of the shoulder joints, which drives the arms upward with some vertical velocity. As the arms pass their anatomical position along side the body and begin to drive forward and up, the trunk also begins to extend. Trunk extension is completed shortly after the arms are raised high above the head. This arm swing in combination with extension of the trunk generates an equal and opposite force that pushes down on the lower body and forces the knee and hip extensor muscles into a more forceful eccentric contraction which preloads them for extension. At this point, immediately after the pre-stretch, the hip, knee and ankle joints begin to extend, reaching peak angular velocities in that order immediately at take-off. At the instant of take-off, the athlete's arms should be fully extended above the head in order to maximize the height of the center of mass at take-off and to ensure that the center of mass accelerates upward reaching a high vertical linear velocity at take-off. This is to ensure high ground reaction forces.

Another study from the University of Amsterdam explains the theory that poly-articular (multi-joint) muscles can perform energy transfer from one joint distally to another (Vergroesen & Van Ingen Schenau, 1982). It proposes that the angular velocity of plantar flexion occurring about the ankle joint does not necessarily reflect the velocity of the gastrocnemius because it is a two-joint muscle (Figure 2.9b). In the kinetic link, knee extension will influence the performance of the gastrocnemius in its role as a plantar flexor. Vergroesen & Van Ingen Schenau (1982) proposed that part of the power during plantar flexion originates from contractions of the hip and knee extensors and is transported to the ankle joint via the rectus femoris (Figure 2.9a) and the gastrocnemius (Figure 2.9b). During plantar flexion of the ankle joint, the knee and hip joints exhibit high angular velocities through extension. This results in slower shortening velocities of the rectus femoris and gastrocnemius because, as they shorten from the distal end, they are lengthening at the proximal end. This produces the slower shortening velocities, and according to the force-velocity relationship, these two-joint muscles are able to generate much higher amounts of force.

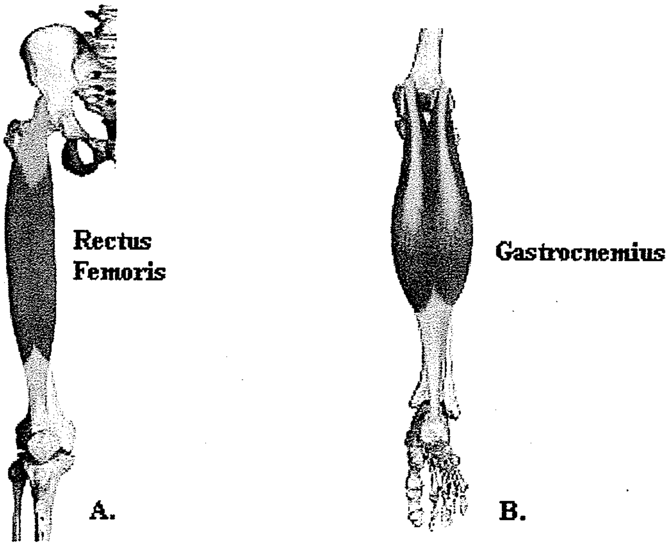


Figure 2.9: poly-articular muscles a) rectus femoris crossing the knee and hip joints and b) Gastrocnemius crossing the knee and ankle joints

In contrast, research has been done to negate the idea of power transfer during the volleyball spike jump. Power transfer refers to the idea that, in a two joint system, the more distal joint can generate greater power due to muscles that cross both the proximal and the distal joint. For example, as the knee joint extends, the gastrocnemius is lengthened and undergoes tension so that when the more distal ankle plantar flexes, the gastrocnemius can again contract more forcefully as a result of stored energy within the series elastic component of the muscle. The take-off characteristic of the spike occurs at a highly accelerated rate. Extension of the knee and hip occurs almost simultaneously along with the plantar flexion of the ankle. According to the study conducted at the University of Amsterdam (Van Ingen Schenau et al., 1985), during the peak plantar flexion velocity of the ankle, both the hip and knee joints are already extending at or near their maximal angular velocities. Therefore, it is questionable as to whether or not there is significant power to be transported.

The arm swing also plays a key role in force production during the take-off phase. The arms begin by flexing downward, passing by the hips and beginning to drive upward.

They reach their peak angular velocity at around the same point that the knees reach their maximum amount of flexion during the crouch. This is because as the arms drive upward, they generate an equal and opposite force that pushes downward on the lower body. This forces the knee joints into greater flexion and causes them to stiffen. Stiffness is a measure of how much deformation occurs under a given amount of force (Nordin & Frankel, 2001). In this case, the less flexion occurring at the knee joint as a result of the downward force of the body, the stiffer the joint would be considered to be. This increased stiffness of the joints elicits a more forceful eccentric contraction in the quadriceps and later a greater stretch-shortening cycle. The arms are also important in increasing the height and vertical velocity of the center of mass at take-off. They do so by continuing to swing upward right up until the instant of take-off.

Ideally, according to Maxwell (1982) of the University of Calgary, "if the body's center of mass is to reach maximum speed vertically and hence maximize the height of the jump, the speeds of the body parts involved in the acceleration must reach their maximum at the same time and as close to the instant of take-off as possible" (p 46). This includes the action of the arms. "The use of the arms must be such that at the end of the accelerating effect of the ankle, knee and hip extensors, the center of gravity of the arms has also achieved its maximum linear velocity in the Y-direction, the intended direction of the jump" (Maxwell, 1982, p 46). Although shoulder angular velocity may be lower at take-off than it was earlier on, the vertical velocity of the center of mass of the arm reaches its highest velocity near take-off.

Luhtanen and Komi (1978) analyzed the contribution of different body segments to the forces acting on the center of gravity of the whole body. Using force platform measurements and cinematography to determine the relative contributions, they found that average take-off velocity of the center of gravity was only 76% of the theoretical maximum calculated from segmental analysis. The use of optimal timing of each segment was calculated to increase the efficiency to 84%. It is a common error for volleyball players to reach their maximum vertical velocity fractionally before take-off indicating that they did not profit fully from a complete and powerful extension of all body parts (Sampson & Roy, 1976).

Arm-Swing

Feltner, Fraschetti, and Crisp (1999) have done extensive research regarding the importance of the arm-swing during vertical jumps. Their findings, although not tested specifically on the volleyball spike take-off, are relevant to the similar mechanics present in the volleyball spike. They found that an arm-swing that results in a body position of extreme shoulder flexion and elbow extension at take-off (Figure 2.10) would increase the take-off height of the center of mass of the body, thereby increasing the height of the jump. In addition, the motion

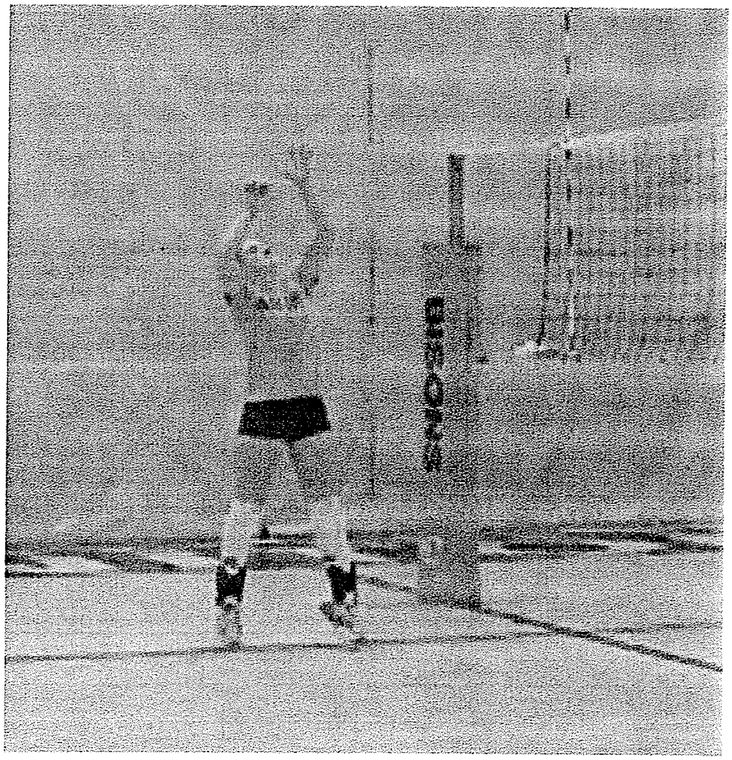


Figure 2.10: Full shoulder flexion and elbow extension is ideal at take-off. Athlete in photo does not demonstrate this ideal technique.

of the arms may also affect the magnitude of the vertical component of the ground reaction force, thus enhancing the propulsive impulse exerted back up on the jumper. According to Newton's third law of motion, "for every action there is an equal and opposite reaction" (Hall, 2003, p 398), the upward force generated by the arm swing must produce an equal and opposite force downward through the body and into the ground. The larger the impulse down, the greater the reaction force upwards and therefore, the greater the vertical velocity of the center of mass of the body at take-off. A third advantage of the arm-swing, as suggested by Feltner et al. (1999), is that when the knees, hips, and ankles are 'coiled' into the optimal crouch position to exert vertical ground reaction forces, the upward acceleration of the arms creates a downward force on the body at the shoulders that increases the magnitude of the eccentric contraction of the quadriceps and gluteal muscles. This results in a large increase in tension within the knee and hip extensor muscles, delaying the concentric contraction that immediately follows. The muscles are placed on a pre-stretch that will effectively increase the force of the concentric contraction thus increasing vertical ground reaction forces.

OUTDOOR APPROACH

The technique used for jumping in the sand is somewhat different from that which has been discussed for jumping on the hard surface of the indoor court. On hard surfaces, jump performance depends largely on the ability to convert horizontal speed and momentum into vertical power. Sand is however, much softer and it absorbs much of that energy before a hitter is able to reach his or her take-off point (Wells, 1996). As a result, peak height attained by jumping on soft sand is much lower than it would be on the hard wood court of the indoor game.

One of the major differences in the game of beach volleyball is that the length of a player's approach will vary significantly with every play. In doubles, with only two players splitting the court, one may be forced to dig the ball from 8 meters from the net and then approach 7-8 meters to hit the ball. This is not characteristic of the more predictable 3-step approach used in indoor volleyball. However, just like the indoor game, a player's approach should always end with the same three steps. These include a shorter directional step to help adjust to where the ball is set and then a longer and higher final step-close into the plant (shown in Figure 2.11).

Figure 2.11: Approach and plant of outdoor spike

Wells (1996) considers the long, fast indoor approach to be rather counterproductive on the beach resulting in a waste of energy and inefficient jumping technique. He suggests that because the sand surface is much softer, it is unable to provide the appropriate braking forces to decrease horizontal momentum and therefore, a fast approach becomes counterproductive.

Figure 2.12: Arm swing from max hyperextension through crouch position and into take-off

In the outdoor spike approach it is very important to use an effective arm swing as the athlete drives up through take-off. This is often accompanied by a forceful extension of the trunk. In the indoor game, athletes can often perform the spike without a large arm swing as their legs are strong enough to jump high enough. On the sand surface however, such a significant percentage of energy is lost in the sand that the athlete must maximize force production as much as possible in the vertical direction. This requires driving the arms up through the crouch position and continuing up until after take-off (Figure 2.12). It is an even more critical concern of beach volleyball players to find a way to limit horizontal velocity at take-off while maximizing vertical velocity. This is very difficult to do with the poor braking forces that the sand applies back on the athlete at foot plant.

Figure 2.13: Illustration of smaller braking forces resulting from energy absorbed and lost in the softer sand surface. (Front view)

A loss of braking forces due to energy lost in the sand surface is shown in Figure 2.13.

There are some subtle differences in the mechanics of the indoor and outdoor volleyball approaches. Due to the softer sand surface, players cannot often use the same explosive joint movements that they would on the harder wood surface of an indoor court. Indoors an athlete is able to use a fast approach and still decrease horizontal velocity during the foot plant. If an approach of this same speed were used outdoors, the athlete would continue to slide forward through the sand. Timing is also more difficult when approaching through the sand surface. Inconsistencies in the sand can lead to unpredictable difficulties when trying to move the feet through its depths as well as when trying to extend out of it during take-off. Often, the initial concentric contraction of the hip and knee extensors drives the feet deeper into the sand as opposed to driving the body upwards. This mistiming of contraction can result in higher angular velocities at the knee and hip joints, however a less efficient use of force production and therefore, lower vertical velocities of the center of mass.

A study by Bishop (2003) tested 18 beach volleyball players performing a countermovement jump on both the indoor and outdoor surfaces and found that all jump heights were significantly lower when performed on the sand ($p<0.05$).

In a related study by Barrett, Neal, and Roberts (1998) the dynamic loading response of surfaces encountered in beach running were examined using drop weight tests on two sand surfaces of different stiffness. For dry sand with a depth of 250 mm and low stiffness, slightly shallower to that of an outdoor volleyball court, they measured low peak forces (~1 kN) for different masses dropped from various heights, and high amounts of penetration into the sand (~50 mm). On the other hand, wet compacted sand, with a medium stiffness was associated with much higher peak forces (~3.5 kN), and small penetrations into the sand (~10 mm). The dry, uncompacted sand and wet compacted sand are classified differently on a continuum from extremely soft and compliant on one end to extremely non-compliant and rigid on the other. The dry compacted surface is comparable to the stiffness of a synthetic surface overlying concrete sub-strata.

Barrett et al (1998) also measured the impact time over which these peak impact forces were absorbed by the surface and found a much longer duration of impact with the dry uncompacted surface (49 ms) versus the wet compacted surface (14 ms). It can be assumed that the wood surface of an indoor volleyball court would show a significantly lower impact duration than either of these. Impact duration is important as it suggests how much time is spent absorbing the force of impact with the surface and can help predict the outcome of the impulse applied by the athlete. Since impulse is equal to the change in momentum of the drop masses before and after impact, the same quantities of momentum need to be overcome for the same initial conditions on each surface. The impulse applied to the striker must therefore be similar for the two surfaces in order to yield the same end result. However, to overcome the momentum of the striker, the wet sand surface applies larger forces over a much shorter period of time, while the dry (softer) sand surface produces a smaller impulse of less force over a much longer period of time.

Because momentum is conserved before and after the collision, the momentum of the drop mass as it impacts the ground is equal to the momentum of the rebounding mass plus the sum of the momentum of each individual grain of sand that has some velocity in the opposite direction after impact. The softer the sand surface is, the greater the downward momentum of the sand will be at contact and therefore, the lower the resulting upward momentum of the drop mass will be. This also illustrates an inverse relationship between the force acting on the striker and the time of impact, the shorter the impact time is with the ground, the greater the amount of force that can be applied to the striker. This can be generalized to a spiker landing in the sand during the plant phase of the spike approach or when landing after contact. Lower impact forces over a longer period of time suggest a decreased risk of injury for outdoor volleyball players who repeatedly land on a soft, dry sand surface, which dissipates much of those forces during the foot plant phase prior to takeoff. Smaller ground reaction forces are therefore applied back on the tissues of the lower body. However, this will also result in a loss of performance relative to the indoor spike approach.

A number of studies examining the interaction of the human body with surfaces of different stiffness have been conducted on elastic or viscoelastic surfaces such as gymnastics mats (Arampatzis, Stafilidis, Morey-Klapsing, Bruggemann, 2004; Farley, Houduk, Van Strien, Louie, 1998; Ferris & Farley, 1997). However, a sand surface is very different in its response to loading as it is not elastic by nature and once deformed will remain so. As a result there is no rebound effect of the sand (positive mechanical work) pushing up on the body. A study conducted by Arampatzis et al (2004) examined the interaction of the human body and surfaces of different stiffness during drop jumps. The surfaces used were two types of gymnastics sprung floors both possessing viscoelastic properties. As a result, they found higher jump heights on the softer surface that also corresponded with a greater deformation of the surface, greater energy storage on the surface and a higher amount of energy returned from the surface to the subject. The energy loss due to surface viscosity during the loading-unloading phase was only about 25 % of the energy transmitted to the surface originally. Sand surfaces do not possess these elastic properties and lie much lower on a softness continuum. It has been suggested that when performing a spike approach and jump on a soft uncompacted sand surface, the surface absorbs almost 100 % of energy (Bishop, 2003; Wells, 1996). However, the possibility still exists that the human body has the natural tendency to increase its own lower leg and joint stiffness proportionally to any decrease in surface stiffness. (Arampatzis et al, 2004).

Soft, compliant surfaces such as sand have also been shown to result in increased eccentric muscle activity of the lower leg (Barrett et al., 1998). As suggested by Arampatzis et al (2004), this may be caused by an increased stiffness at the joints of the lower legs as the body reacts to a soft surface of low stiffness. When changing the stiffness of a surface, the human body adjusts its behavior to the surface that it is interacting with. A decrease in surface stiffness causes the body's neuromuscular system to trigger an increase in leg and joint stiffness by increasing the co-contraction of muscles crossing the knee and especially ankle joints. Leg and joint stiffness are defined as the ratio of force to linear displacement of center of mass, or joint moment to angular displacement (Farley et al., 1998). As a consequence the mechanical work done by the subject is reduced, while the mechanical work of the surface is increased (Ferris & Farley, 1997).

A study by McMahon and Greene (1979) suggested that the performance of an athlete can be enhanced by altering the stiffness of the running track to the stiffness of the human body. They found that running performance decreases if the surface stiffness falls below the stiffness of the body. The negligible spring stiffness of soft sand may therefore explain decreases in not only maximum running speed on soft sand but also decreases in peak jump height.

Increases in leg stiffness during jumping can have devastating effects on jump performance on a sand surface with no spring characteristics. Increased stiffness results in a decrease in the vertical displacement of the body's center of mass relative to the surface (Ferris et al., 1997). A decrease in the vertical displacement of the center of mass and in the angular joint displacement of the knee and hip joints reduces the amount of force that the subject can deliver during the jump and therefore reduces take-off velocity.

The spike approach used in beach volleyball usually consists of a much slower approach with a lower horizontal velocity. This allows the length of the final step into the plant phase to be shorter with less horizontal velocity so that during takeoff all force may be directed vertically. If the horizontal velocity of the approach were equal to that of the indoor spike approach, then when the outdoor athlete plants his/her feet into the sand the center of mass would have a larger horizontal force component and the sand would not be able to apply enough force back against the foot in order to decrease horizontal momentum. Too much force is lost in the movement of the sand. The arm swing also plays a more critical role in the outdoor spike approach as it is used to direct forces in a vertical direction as opposed to horizontally. It is also important to force the joints of the lower body into greater amounts of flexion and a more forceful eccentric contraction. When performing the indoor spike approach, the athlete can usually get away without this concern, as some horizontal drift in the air is acceptable because it allows the athlete to increase linear velocity of the hand at contact. In the indoor game, the athlete also enters the plant phase with a much greater horizontal velocity. In a sense, the force with which the ground pushes back on the athlete when the feet are planted out in front plays the same role that the arm swing does. It acts to increase the magnitude of the eccentric contraction that occurs in the quadriceps muscle group, therefore generating a much more efficient stretch-shortening cycle and a greater concentric contraction during the take-off phase. However, this is not possible in outdoor volleyball. As mentioned, an increase in the horizontal velocity of the center of mass is not possible in the sand, as it is not able to apply enough braking force back on the athlete. As well any increase in horizontal velocity must yield a decrease in the vertical velocity if the take-off velocity is to remain the same. In outdoor volleyball, the athlete cannot afford this loss of vertical velocity as it results in a lower height jumped. Therefore, the outdoor athlete needs to consider all of the mechanics of jumping that help to increase vertical velocity while reducing horizontal velocity. By driving the arms up with a higher velocity, the athlete can still create a force that pushes downward on the lower body increasing the magnitude of the eccentric contraction that occurs during the crouch position of maximum knee and hip flexion.

It is also common in the outdoor spike approach to witness a greater amount of trunk flexion in the crouch position and then more forceful trunk extension as the athlete pushes upwards into take-off. For the same reasons as the arm swing this also increases the downward force on both the lower body and the ground. The force on the lower body again increases the magnitude of the contraction in the quadriceps muscles while the force on the ground increases ground reaction forces that push up on the athlete.

VIDEO ANALYSIS TECHNIQUES

Many researchers use video analysis to study particular skills or movement patterns associated with various sports. A large majority of these skills and movements occur at velocities that are far too fast for the human eye to critically observe. Video allows the observer to view the performance one frame at a time and break the skill into various components much more effectively.

There are several advantages to using video, some of which include: the low cost of videotapes, the images are immediately available for analysis, and filming procedures can easily be adjusted on site immediately after viewing the video. One major drawback of video is the speed at which the movement is filmed. High-speed cameras capture film at 200 frames per second or greater. Standard video taping can only record at 30 frames per second that can later be broken down and enhanced slightly further to 60 frames per second (Peak Technologies, 1994). However, 60 frames per second is acceptable for the analysis of most sports skills. High speed video cameras that allow experimenters to capture more than 60 frames per second are currently available but their cost is prohibitive.

The most recent development in video analysis is the use of digital video cameras for capturing video. A digital camera is similar to an analog camera except that the film is replaced with an electronic sensor. The sensor is comprised of a grid of photo diodes, which change the photons that strike them into electrons. The electrons are stored in small buckets (capacitors) which are read out as a series of varying voltages, which are proportional to the image brightness. The voltage is converted to a number by an Analog to Digital Converter and the series numbers are stored and processed by a computer within the camera (Nice & Gurevich, 1998).

DARTFISH VIDEO ANALYSIS SOFTWARE

The Dartfish video analysis software, used today for the analysis of athletes in a variety of sports, was introduced in 1997 when SimulCam™ technology was created at the Swiss Federal Institute of Technology in Lausanne, Switzerland (Dartfish, 2005). In December 1998, InMotion Technologies Ltd. was formed to commercially develop SimulCam™ and other digital imaging applications. In 2001, the company grew in its involvement as a sport training application and became known as Dartfish and continues to distribute software packages including DartTrainer and DartGolfer. Over the years, Dartfish has become increasingly involved in the development of analysis of numerous sports, winning many awards for its innovative technology.

Dartfish is the official video performance analysis software provider for USA Volleyball. Doug Beal, Head Coach, USA Men's Volleyball team stated that, "the DartTrainer is the perfect training tool for coaches at all levels" (Dartfish, 2005).

The Dartfish DartTrainer software is used for the analysis of sports techniques, but more accurately the comparison of athletes' techniques. The software possesses several tools to facilitate the biomechanical analysis of sport skills. The original SimulCam™ technology that Dartfish was based on is the first technology that can take two video clips of separate athletic performances and superimpose one athlete over another in the same background creating a new high quality video clip for in-depth comparison and analysis. In 2001, the StroMotion™ analysis tool was added to Dartfish technology. StroMotion™ breaks down a moving object into a frame-by-frame sequence to highlight position and trajectory. The program also offers the analysis tools of zooming in on objects, making accurate distance conversions by marking a known length in the film, which can be used for the calculation of linear and angular displacements. In addition to the ability to measure these displacements, a frame counter is also provided by the system to measure time elapsed and can be used to calculate both linear and angular velocities. Finally, the software provides an abundance of drawing tools that can be used to accentuate and present valuable points of emphasis within the skill. To name a few, these include: an angle drawing tool, square/circle features, arrows, text, and a spline tool that allows one to track the path of a moving object in a linear or curvilinear path.

PEAK 5 DATA ANALYSIS SOFTWARE

The Peak 5 Data analysis software, designed by Peak Performance Technologies (1994) is a system used for the quantitative analysis of athletes. It allows the researcher to produce a three-dimensional stick figure representation of an athlete performing a skill. This is done through the precise calibration of two or more video cameras which are genlocked (synchronized) with one another to ensure that the filming of each camera starts at the exact instant and that each frame recorded lines up with the other camera. Then a calibration tree is filmed by each camera simultaneously from two or more angles. 24 different points on the tree, of known distance from one another, are manually digitized into the system by the observer and are used to calculate distance conversions for each camera. The calculations from this three-dimensional calibration tree are important to create a three-dimensional space in which the skill will be performed.

Calculations of movement that occur within the span of these 24 digitized points that form the calibration tree can be determined accurately.

The video collected from these cameras is independently entered into the Peak 5 data analysis software through a digitization process where the experimenter manually identifies each joint and segment position by clicking on each of 21 points specified in a spatial model of the athlete for each frame of film. The Peak 5 system can then track any changes in the position of these points independently or relative to one another. This will provide all segment and joint displacements as data that can be collected and analyzed. The system can also calculate these linear and angular displacements with respect to time and use that information to present the experimenter with linear or angular velocity data, and accelerations.

All data provided by the Peak 5 software can be made available to the experimenter in either table format or can be graphed individually or in combination with other data. This provides a clear graphical illustration of results and comparisons to the experimenter for presentation.

DATA SMOOTHING

A technique commonly used in video analysis is data smoothing to filter out inaccuracies caused by human error or lack of technical precision.

The Peak 5 Video Analysis system contains a Data Conditioner program. The data conditioner program allows one to filter the paths of each digitized point in each of the dimensions. Random amplitude noise that may have been created during the digitizing process can be filtered out using a digital filter. The Peak 5 Video Analysis system digitizes pictures at a rate of 60 Hz; therefore, the error resulting from digitizing occurs at a constant rate, but with varying levels of amplitude. Filtering will reduce the likelihood of calculating unrealistic values during data collection. For example, outliers may possess rather high or low velocities as compared to the rest of the points surrounding it. Filtering smoothes out the data so that outliers will not have a dramatic effect on the results of the study. It is very important to be cautious of over filtering, as it will eventually begin to reduce important peak accelerations and velocities. Maximum and minimum values will be underestimated. For example, peak vertical velocity of a spiker's center of mass at take-off may be calculated to be much lower than it actually is due to overly extensive smoothing of the data.

The Peak system possesses three different filters for smoothing data: The Butterworth Filter, The Fast Fourier Transform (FTT) filter, and the Cubic Spline filter. The Butterworth Filter is an all-purpose filter used to filter out the constant error resulting from digitization of video. The FTT filter is used to filter out random noise and is used most often when the skill is cyclic in nature and the Cubic Spline filter is best for filtering movement that is parabolic, such as a golf swing (Peak Performance Technologies, 1994). The number of passes that a filter makes across data determines the amount that the data is smoothed, however too many passes will result in inaccurate data. Usually, about 2-4 passes are optimal for smoothing data and maintaining the maximum and minimum values of each data point within a skill.

CHAPTER 3

METHODS

The purpose of this study was to identify kinematic differences between the outdoor volleyball and indoor volleyball spike approach and take-off. This analysis will produce some coaching implications that will help to minimize the decrease in jump height during spiking commonly experienced in beach volleyball. Several tools were used in the analysis including three-dimensional filming and video analysis of both the indoor and outdoor spike approaches. Film analysis of each skill was performed using both the Peak 5 Technology as well as the Dartfish DartTrainer software in order to measure performance differences between the two spike approaches and determine differences in the biomechanics that may be causative factors for any performance differences that occur.

Subjects

For this study, ten elite female indoor and ten elite female outdoor volleyball players were selected from across Canada. Indoor athletes were highly skilled and recruited from the Canadian Women's National Volleyball team and the University of Manitoba Women's Volleyball team. Outdoor players included elite female competitors filmed at the 2004 Senior Open National Championships in Beach Volleyball held in Wasaga Beach, Ontario in September, 2004. All subjects were highly experienced volleyball players competing in the sport for over eight years. The athletes were required to attack the ball from the left side position of the court and therefore, were all right hand dominant. All had experience competing from this position on the court. Each athlete reported no injury in the past year that could hinder her jump performance during testing.

Prior to the filming session, all outdoor players who had past experience in both the indoor and outdoor sports were asked to explain to the camera what they felt were some key differences in the biomechanics of the indoor and outdoor spike technique. From experience, the athletes gave their thoughts and opinions of which key variables, if any, they found differed in the sport of beach volleyball. This information was used to help identify which variables would be of most importance and to further understand the awareness of the athletes in regards to any technique changes that need to be made when transitioning from the indoor to the outdoor game.

Ethics approval was obtained from the University Research Ethics Board prior to the collection of data (Appendix A). All subjects were also required to provide written informed consent prior to being filmed for the study. A sample consent form is included in Appendix B.

Filming Technique

Each athlete was filmed in a controlled setting away from actual competition in order to control for variables such as game strategy involving variability in the opposition's defense, and variations in the set delivered to the attacker. The controlled setting was also used to further optimize the angles of view available to the cameras and to eliminate any possible interference or distractions from the view of the hitter. Two digital video cameras (Canon ZR50 and Canon Optura 500) were used for the filming of the skill, each filming at a speed of 30 Hz or 30 frames per second. The cameras were set up at equal distances from the athlete and at 90-degree angles to each other.

For the purposes of this study and to reduce variability, only cross-court attacks from the left-side position of the court were used for analysis. A minimum of five complete spike approaches per athlete were captured on film. From these, the successful trial yielding the highest displacement of the center of gravity from take-off to peak height (peak height jumped) was chosen for analysis. A successful trial was characterized by the ball landing cross-court in the designated target area, with no hitting error on the play (i.e. the athlete contacting the net). Figure 3.1 illustrates the camera set-up that was used for video capture as well as the approximate path of the attacker and the target area that the ball was required to be hit into in order to designate a successful attempt (position 5 on the indoor volleyball court).

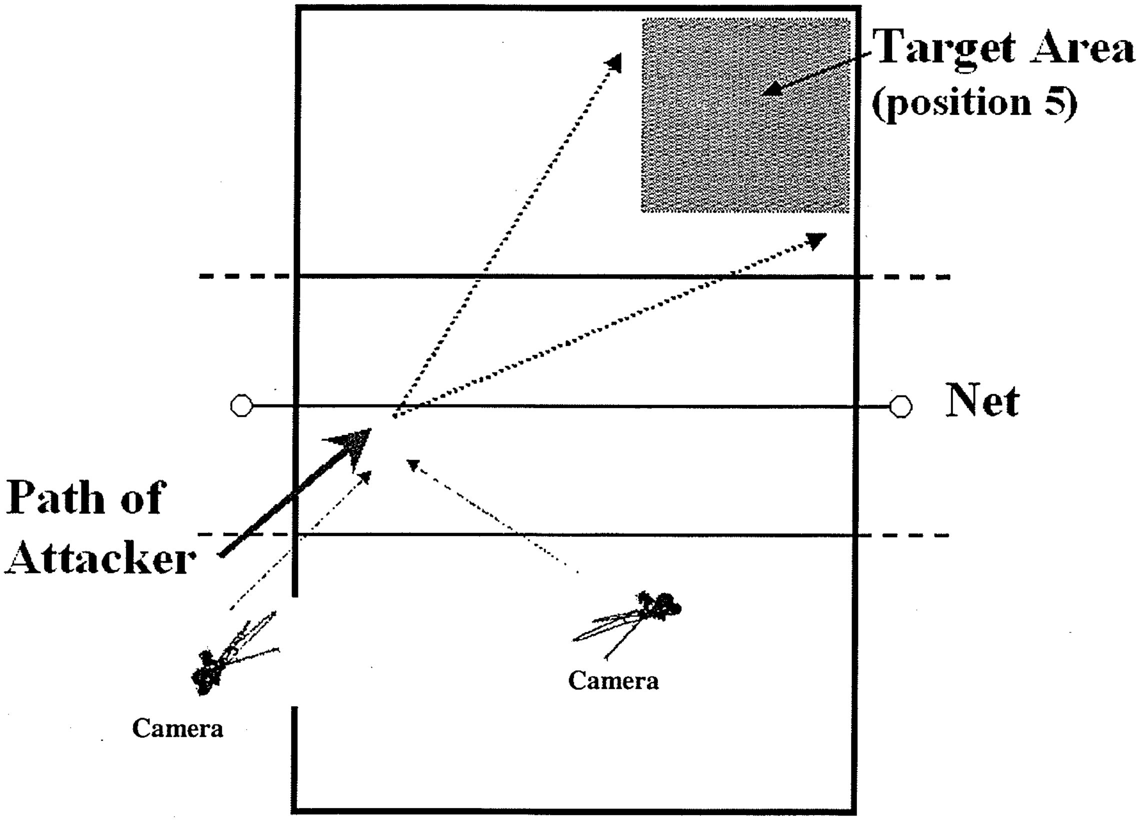


Figure 3.1: Filming environment illustrating camera set-up, path of attacker, and target area that designates a successful attempt.

Camera 1 (Canon ZR50) was situated on a tripod in such a way that it captured a purely sagittal view of the athlete's right side. This was done to help ensure accurate measurements of joint angles and velocities later during analysis. Camera 2 (Canon Optura 500) was placed on a tripod perpendicular to camera 1 in order to capture a posterior view of the athlete that could be used for three-dimensional analysis using the Peak 5 Performance System. Each camera was manually focused with a shutter speed of 1/500, to ensure that no blurring of the image would occur. A fast shutter speed is ideal for the filming of sports skills involving high speed movements as it exposes the film to light for a shorter period of time. However, this requires an adequate amount of light that must be taken into consideration in the filming environment.

Following camera set-up, the cameras were calibrated using a calibration tree from Peak Technologies. The calibration tree (Figure 3.2) consists of eight rods screwed into a metal block and placed on a tripod. Each rod contains three reflective balls at a known distance from one another. The calibration tree needed to be assembled and placed directly over the position where the subject would plant her feet on the last step of the approach in preparation to jump. Only movements occurring within the span of the calibration tree could be accurately measured using the Peak system. Any movements that occur outside of the tree's diameter are susceptible to errors and were only carefully used for calculations. Video analysis within the volume of the calibration tree is precise enough for most practical purposes (Angulo & Dapena, 1992).

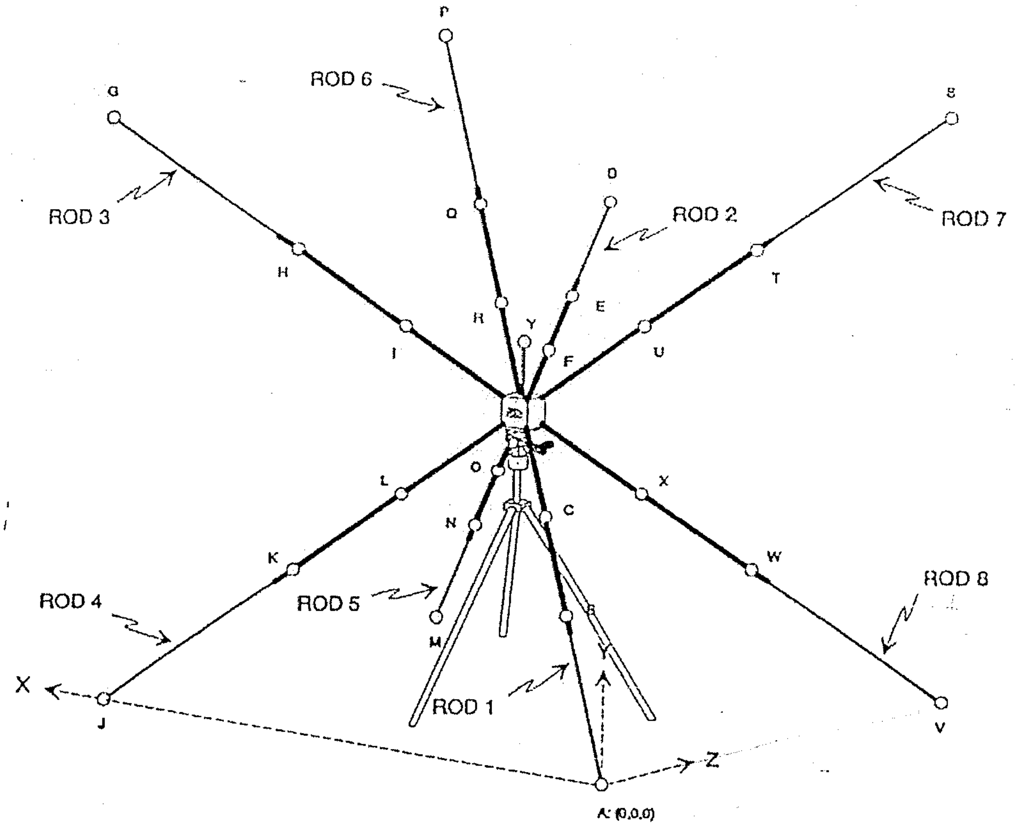


Figure 3.2: Model of calibration tree (Peak Performance Technologies, 1994)

Video Analysis

Video analysis was used to gather quantitative information regarding the biomechanics of the indoor and outdoor spike approaches. The main determinant of jump performance was the peak height of the jump or the vertical displacement of the center of mass from take-off to its highest point in the air. Several variables have been identified in previous literature and mentioned earlier in this paper that affect the peak height an athlete can achieve when jumping. The variables that were measured in this study have been classified into the phases of the spike approach as defined in Chapter 2, and are listed below:

Approach Phase

- Path of center of gravity (horizontal and vertical displacements)
- Position of center of gravity prior to foot-plant of last step
- Horizontal and vertical velocity of the center of mass prior to the last step and at take-off
- Length of last step
- Arm swing – shoulder joint flexion initially and hyperextension nearing the end of the approach

Plant Phase

- Position of center of gravity at initial foot contact used to estimate amount of braking force generated by ground reaction forces
- Time elapsing between initial foot contact and second foot contact to determine type of foot plant (fast/slow step-close vs. hop)
- Peak flexion angles at the trunk, hip, knee and ankle joints
- Angular velocity of the trunk
- Angular velocity of the arm swing as the shoulders flex
- The timing between peak angular velocity of the arm swing and maximum knee flexion

Take-Off

- Angular displacements and velocities at the shoulder, trunk, hip, knee and ankle joints
- Peak angular velocities at the trunk, hip, knee and ankle
- Timing of peak segmental angular velocities (hip, knee, and ankle)
- Vertical and horizontal velocity at take-off
- Position of the center of gravity in the y-direction relative to body height

Airborne

- Height jumped as measured by the displacement of the center of mass from take-off to peak height
- Height of contact. The height of the hand as it contacts the ball, as measured from the ground.
- Amount of horizontal drift

In order to maximize the height of the jump, a volleyball player needs to increase the vertical velocity of the center of mass as much as possible prior to take-off. The vertical velocity of the center of mass is directly related to the height of the jump and can be used to calculate jump height using two equations:

$$\text{Equation 1:} \quad T_{up}=\frac{Vv}{g}$$

Where T_{up} is equal to the time up that it takes to reach peak height measured in seconds; Vv is the vertical velocity in meters per second; and g is equal to the downward pull of gravity in m/s^2. The time up calculated from equation 1 can then be used to determine the peak height of the jump using equation 2.

$$\text{Equation 2:} \quad s = \tfrac{1}{2} gt^2$$

Where s is equal to the distance the center of mass will travel upwards to peak height in meters; g is again the acceleration due to gravity; and t is the time up from equation 1.

These equations were used to verify the data provided by the Peak 5 software regarding jump height and the vertical velocity at take off. These equations provide a good verification of the data collected.

The video analysis for this study was conducted primarily using the Peak Performance Technologies (1994) software with some use of the Dartfish DartTrainer® software for qualitative comparisons and illustrations between spike approach conditions.

The Peak Performance Technologies (1994) system used for analysis consisted of the Peak 5 software (version 5.2), a Sanyo GVR-SP55 video cassette recorder (Sanyo, Compton, California), a Sony Trinitron PVM 1341 color video monitor (Sony corporation, Ichinomyia, Japan) an ALR IBM compatible personal computer (ALR Technologies, California), a NEC MultiSync 2A computer monitor (NEC Corporation, Tokyo, Japan), a Hewlett-Packard Laser Jet Series II printer and a Hewlett-Packard 7474A plotter printer (Hewlett-Packard Company, San Diego, California).

Video from each of the 20 spike approach trials was imported into the Peak 5 Performance system for analysis. The Peak 5 system is a tool used in the quantitative analysis of human movement. It allows the researcher to convert the skill to be examined into a 3-dimensional stick figure representation of the subject. From this stick figure, data regarding linear and angular displacements, velocities, and accelerations can be acquired with precise accuracy. In this study, the video first had to be transferred from digital video format into analog video format and recorded onto a VHS tape in order to be used in the video cassette recorder supplied with the Peak 5 system. Then, time code was applied to the video using the video encoder included in the Peak 5 software. This was to overwrite the video with an audio tone at a frequency of 60 Hz dividing the video into 60 frames per second that could be recognized by Peak 5.

A spatial model or, computer representation used for a volleyball player was created to represent a 14 segment model of the human body. The spatial model consisted of 21 individual points, which were digitized for every frame throughout the entire spike approach from the data collected by the sagittal and frontal view cameras. The center of mass of the spatial model could be calculated by the computer software and was labeled on the model as point 22. The 21 spatial model points digitized are shown in the spatial

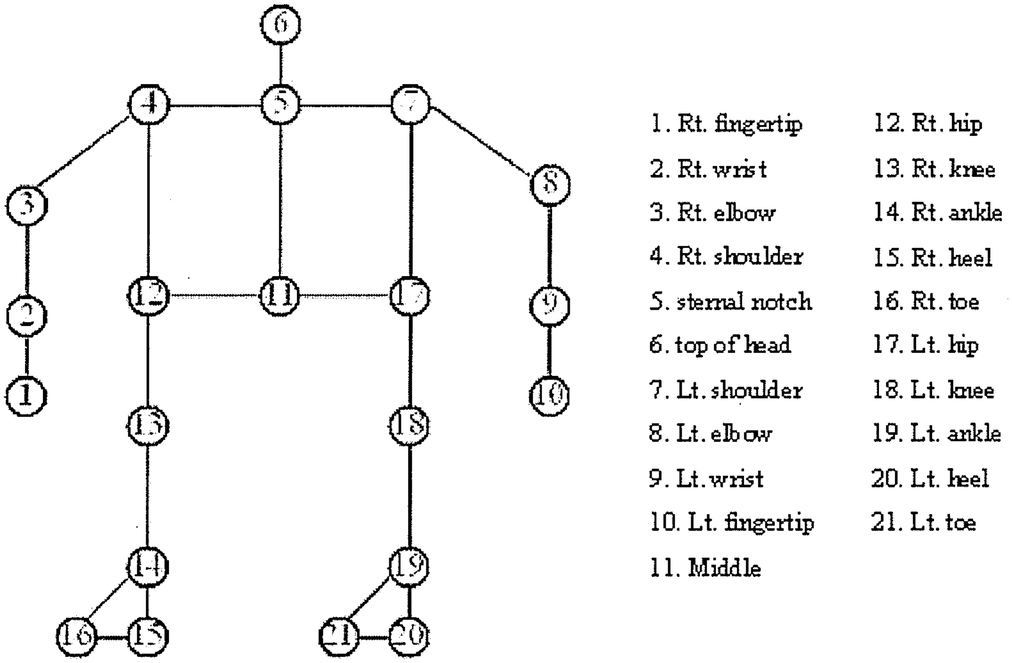


Figure 3.3: Twenty-one point spatial model

model in Figure 3.3. The data from each camera were combined using Direct Linear Transformation (DLT) methods to produce three-dimensional coordinates.

For this study, the measurement of joint angles was performed using the Peak 5 software by connecting a line drawn from the joint center of the axis of rotation along the distal segment and a second line drawn along the proximal segment. The angle was measured at the joint axis where the two lines intersect. For example, a knee joint angle can be computed by identifying the joint center of the axis of rotation of the knee and then connecting a line that runs from the axis towards the joint center of the distal ankle joint and another line from the axis proximally to the ipsilateral hip joint. Angular displacements were calculated as the difference between an initial and final joint angle, and angular velocities were further computed by dividing the angular displacement of the joint by the amount of time that had elapsed over the range of motion. For example, a large angular displacement occurring over a short period of time will yield a high angular velocity.

Horizontal and vertical velocities of the center of gravity are critical variables that were measured during the approach and take-off respectively. The horizontal velocity that the athlete generates during the forward movement of the approach phase is important to increase the linear momentum of the athlete. The athlete must then use the plant phase as efficiently as possible to decrease this horizontal momentum and help to produce vertical momentum at take-off. How efficiently this momentum is utilized is a large determinant of how much vertical velocity the athlete can generate into the instant of take-off (momentum is equal to the athlete's mass multiplied by her velocity).

The Peak Performance Technology (1994) calculates the center of mass for the entire system by considering the position of the center of mass of each individual segment and its contribution to the entire system. By balancing the torque due to each segment, the software is capable of calculating the balance point (center of mass) of the entire body at any point in time throughout the skill. This is known as the segmental method for determining the center of gravity (Hall, 2003).

The Dartfish DartTrainer® software (Dartfish, 2005) was also used in this study to qualitatively compare trials of the indoor and outdoor spike approaches. This qualitative comparison is used to graphically illustrate the findings of the study by placing trials of the indoor and outdoor spike approaches side by side in a split screen format so that differences between the two techniques can be illustrated more clearly than the use of stick figure representations. The software has been installed onto an Intel® Pentium IIII processor and with the use of its several tools for the analysis of sporting skills it was used to present still frame pictures of key points throughout the skill, as well as side by side and superimposed comparisons of the two environmental conditions under which the spike approach was performed. All photos taken and included in this document were produced using the Dartfish software. The same trials analyzed using the Peak 5 Software were imported into the Dartfish DartTrainer® software and used for these comparisons.

Statistical Analysis

Means and standard deviations of all variables were calculated for the ten subjects for each of the indoor and outdoor groups. The variables were compared to each other across conditions (outdoor vs. indoor) using standard t-tests in order to determine whether or not significant differences existed. Finally, listwise correlation tests were performed to determine the relationship between each variable and its effect on jump height performance. This was important to determine whether the variables being compared between groups did in fact have a positive or negative effect on peak height jump performance, measured as the vertical displacement of the center of mass from take-off to peak height.

Finally, a forward stepwise regression analysis was done to determine the set of variables that best predicts jump height in the spike jump for each of the indoor and outdoor spikes.

CHAPTER 4

RESULTS

Following the completion of data collection through the process of video capture and video analysis using the Peak 5 Analysis software, 28 individual variables (listed in Appendix A) were measured for the spike jump for each of the ten indoor and ten outdoor subjects. The Peak 5 software provided accurate measurement for each of these variables displaying only a small amount of error related to the calibration of the cameras and the digitization of joint positions. This information was analyzed statistically using standard t-tests to identify significant differences between indoor and outdoor variables. Correlations were also calculated to determine the relationship of each independent variable with the vertical displacement of the center of mass from take-off to peak height (height jumped). These correlations were determined separately for the indoor and outdoor conditions to determine whether or not different variables were related to jump height. Finally, these variables were placed into a step-wise multiple regression analysis to determine which variables are the best predictors of jump height for the indoor and outdoor conditions.

After statistical analysis, several useful conclusions were drawn including key differences that were found to exist between the two spiking conditions. This chapter will describe each of these findings and the effects of several important variables on the vertical displacement of the center of mass.

Interview Results

Prior to filming, each subject from the outdoor group was interviewed in order to determine what she thought or the key differences, if any, were in the outdoor spike approach and take-off when compared to the indoor spike. All ten subjects described having previous experience playing indoor volleyball and a strong familiarity with the proper indoor spike technique.

The results of the interview data collection are displayed in a chart showing the most common differences as indicated by the ten subjects interviewed (Figure 4.1).

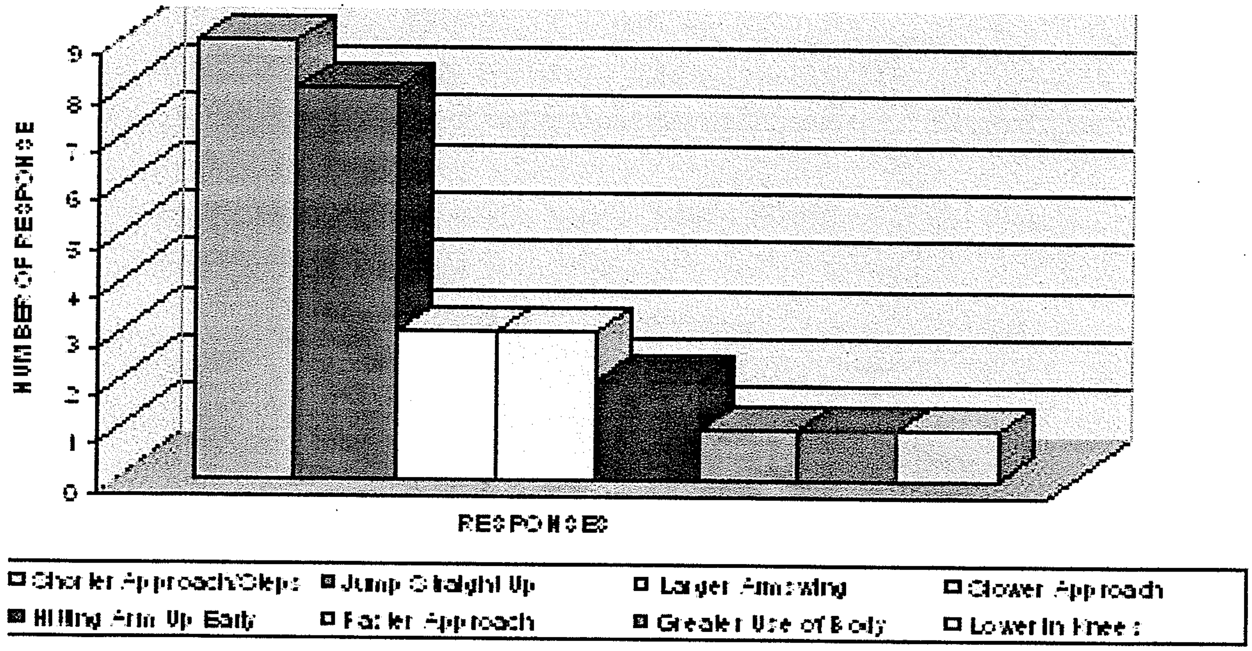


Figure 4.1: Most common interview responses to the differences in the outdoor spike approach and take-off when compared to the technique of the indoor spike.

Vertical Displacement of the Center of Mass

A standard two-tailed t-test was performed on the results produced by the three-dimensional video analysis and showed a significant difference in the vertical displacement of the center of mass between indoor and outdoor spike conditions (Table 4.1). The results confirmed that volleyball players could jump higher on the indoor hard wood surface than on the outdoor sand surface by a mean difference of 0.058 meters (Figure 4.2). Jump height performance was determined using three separate methods to show consistency in results. Table 4.1 also shows the mean vertical displacement of the center of mass, the vertical displacement of the hip joint and the height of contact for each group. The vertical displacement of the center of mass was used as the gold standard for determining jump height while the other two variables can be shown to verify the validity of the findings. Vertical displacement of the center of mass is shown in Figure 4.3 for each of the subjects.

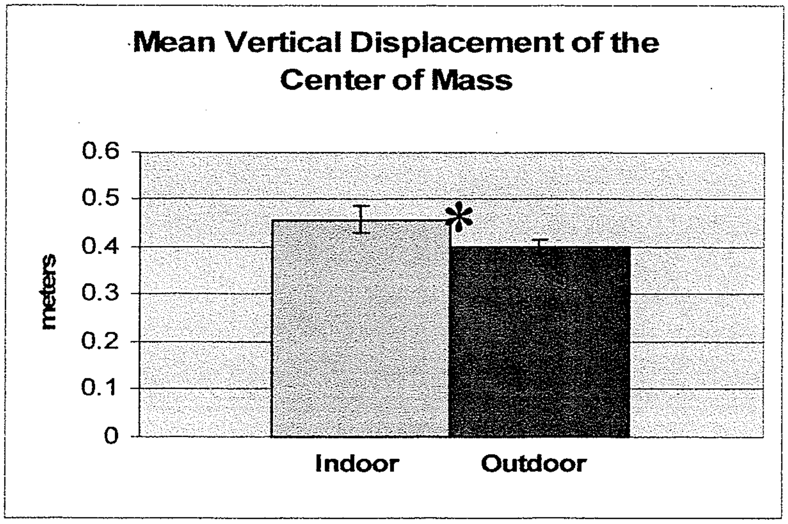


Figure 4.2: Mean vertical displacement of the center of mass between indoor and outdoor spiking conditions

* Indicates significant difference between groups (*p<.05)

Table 4.1: Results of Vertical displacement of center of mass (CM), vertical displacement of the right hip (RH) and height of contact (CO) for both indoor and outdoor conditions.

Variables	**Indoor N=10**		**Outdoor N=10**		**p value**
	Mean	**SD**	**Mean**	**SD**	
Displacement of CM (m)	0.458	0.091	0.400	0.044	0.04*
Displacement of Rt. Hip (m)	0.507	0.100	0.442	0.044	0.07
Height of Contact (m)	2.431	0.141	2.255	0.130	0.01**

*p<.05; **p<.01

Standard t-tests were also performed between each of the 28 independent variables measured in this study in order to identify any significant biomechanical differences between the indoor and outdoor technique used by elite athletes when approaching and spiking the ball. These variables were collected and analyzed in the order that they occur through the spike approach, plant, take-off and airborne phases of the skill.

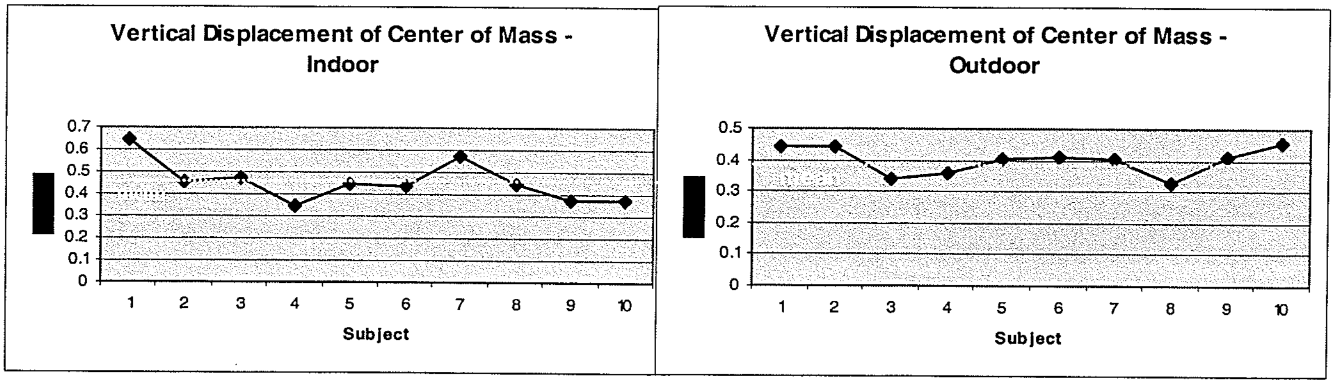


Figure 4.3: Graph showing the results of vertical displacement of the center of mass for all 20 individual subjects including 10 indoor and 10 outdoor. The mean value for each group is shown by a white line.

Approach phase

The approach phase of the volleyball spike, characterized as the time frame from when the athlete begins to move towards the net, (usually a step onto the left foot) until the right foot plants in front of the body, was carefully analyzed using the Peak 5 analysis software. Several variables were measured during this phase and compared statistically between the indoor and outdoor spike trials in order to identify any mechanical differences between the two conditions. Table 4.2 displays all variables measured and the mean values for each between the indoor and outdoor subjects.

Table 4.2: Mean variables measured during the approach phase of the spike for indoor and outdoor subjects

Variables	**Indoor N=10**		**Outdoor N=10**		**p value**
	Mean	**SD**	**Mean**	**SD**	
CM Horizontal Velocity Prior to Plant	3.32	0.30	2.74	0.33	0.001***
CM Vertical Velocity Prior to Plant (m/s)	-0.66	0.33	-0.84	0.30	0.21
Length of Last Step (m)	1.30	0.20	0.99	0.16	0.001***
Peak Shoulder Hyperextension (Rt)	83.58	14.19	81.77	8.28	0.74
Peak Shoulder Hyperextension (Lt)	83.17	22.34	87.58	15.04	0.61

***p<.001

The horizontal velocity of the center of mass prior to the initial foot plant was defined as the horizontal velocity of the center of mass one frame (0.017 seconds) before the right foot contacts the floor during the plant. The t-test showed a significant difference in the horizontal velocity of the center of mass prior to the initial plant (right foot) (Figure 4.4).

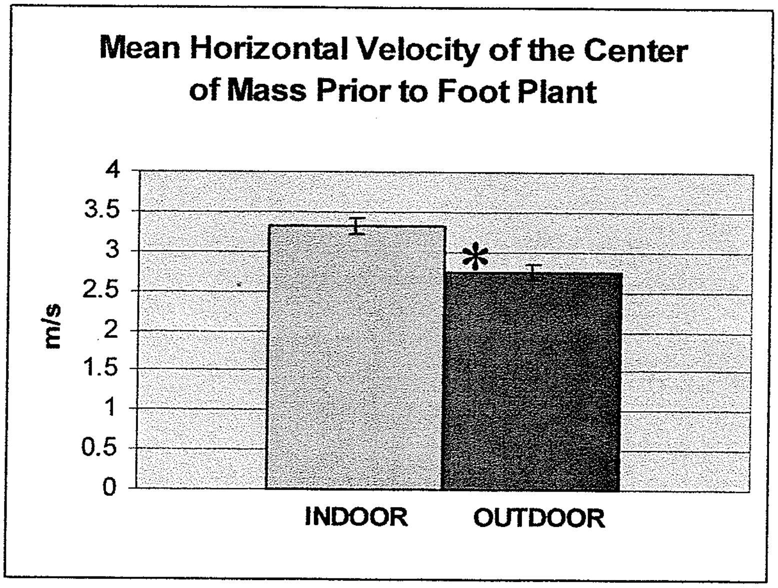


Figure 4.4: Comparison of mean horizontal velocity of the center of mass one frame before the initial plant of the right foot.
(* p<.05)

The vertical velocity of each subject's center of mass was also measured one frame prior to the plant of the right foot and although the means for each of the groups differed slightly with a greater downward velocity of the center of mass for the outdoor subjects, no significant difference was found.

A significant difference was found in the length of the last step with indoor subjects taking a significantly longer last step than outdoor subjects. The last step begins with a push-off from the left foot, driving the athlete forward and into the initial foot plant of the right foot. Figure 4.5 displays the mean step lengths measured for the indoor and outdoor athletes.

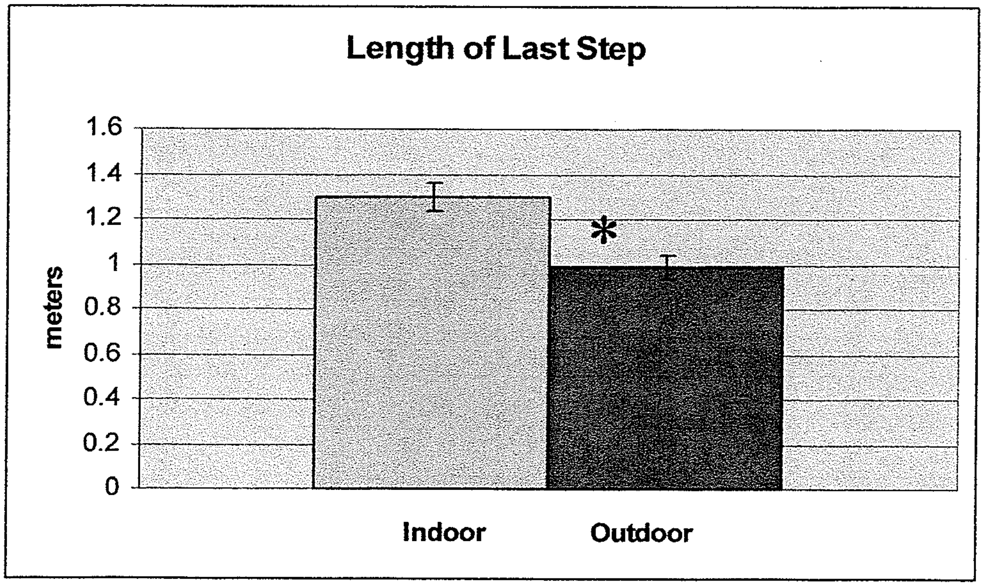


Figure 4.5: Mean length of the last step of the approach as measured for both the indoor and outdoor groups.
(* p<.05)

The final variable measured during the approach phase was the angular displacement of the shoulder joints as the shoulders hyperextend during the airborne portion of the last step. As shown in Table 4.2, all subjects demonstrated between eighty and ninety degrees of hyperextension, however when compared between groups, no significant difference was found. This marked the end of the approach phase, which may also be considered the preliminary movements to the volleyball spike.

Plant phase

The plant phase is described as the period of the volleyball spike that begins after the long last step of the approach, when the right foot plants and continues on while the left foot is brought forward and planted beside the right foot. The plant phase ends with the athlete in a deep crouch position, ready to begin force production. This portion of the plant is often referred to as the backswing phase of the jump.

Throughout the plant phase, several variables were again measured for each subject and tested using standard t-tests to determine any significant differences between indoor and outdoor conditions. The variables measured during the plant phase are listed in Table 4.3 along with their mean values for each of the indoor and outdoor conditions. They are listed and analyzed in the order that they occur during the plant phase of the spike.

Table 4.3: Mean variables measured during the plant phase of the spike for indoor and outdoor subjects.

Variables	**Indoor N=10**		**Outdoor N=10**		**p value**
	Mean	**SD**	**Mean**	**SD**	
Right Heel to CM at Plant (m)	0.29	0.12	0.23	0.07	0.19
Step Close Time (sec)	0.18	0.04	0.12	0.06	0.02*
Time From Plant to Take Off (sec)	0.33	0.04	0.38	0.05	0.02*
Peak Flexion Angle of Knee (deg)	112.76	5.75	113.01	12.63	0.96
Peak Flexion Angle of Hip (deg)	114.04	5.46	109.60	8.53	0.18
Peak Flexion Angle of Trunk (deg)	19.89	5.96	27.22	8.02	0.03*
Peak Shoulder Angular Velocity	612.63	129.59	505.104	140.09	0.09

* $p<.05$

The first variable to be measured was the distance between the heel of the right foot at initial foot plant to the line of gravity of the athlete (FP to CM). This was to determine how far in front of the line of gravity the athletes plant their foot. Table 4.3 shows the mean value for the indoor volleyball players to be only slightly greater than the outdoor subjects. However no significant difference was found suggesting that all indoor and outdoor players plant their foot at close to the same distance in front of their line of gravity.

The step close time was also calculated by the Peak 5 system. Step close time is the duration between the time that the first foot contacts the ground to the time that the second foot closes and plants beside it. A significant difference was found to exist between indoor and outdoor subjects with outdoor subjects planting their feet together significantly faster. The difference in mean values is illustrated in Figure 4.6.

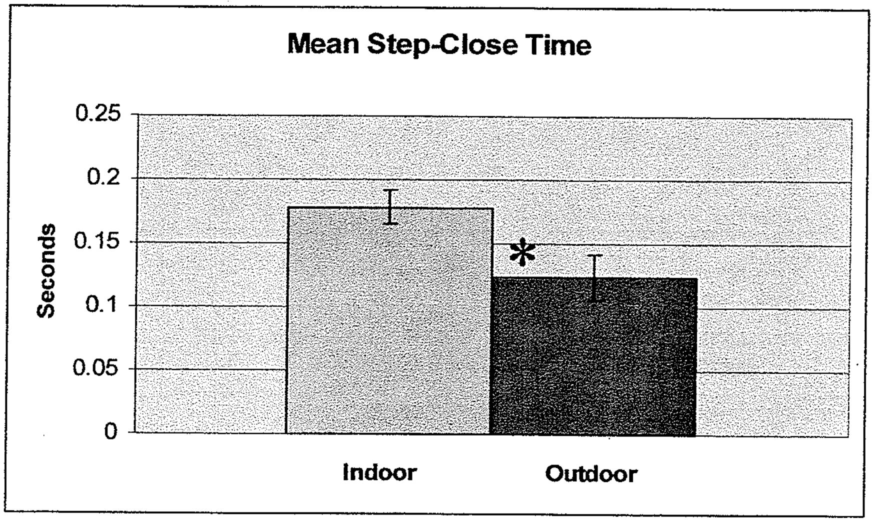


Figure 4.6: Mean step-close time between indoor and outdoor subjects showing significant difference in results.
(* p<.05).

As well as step-close time, the total amount of time spent in contact with the ground was also measured. This was the time from initial foot contact up until the critical instant of take-off. Figure 4.7 shows a significant difference between the means of indoor and outdoor groups when comparing the ground contact time.

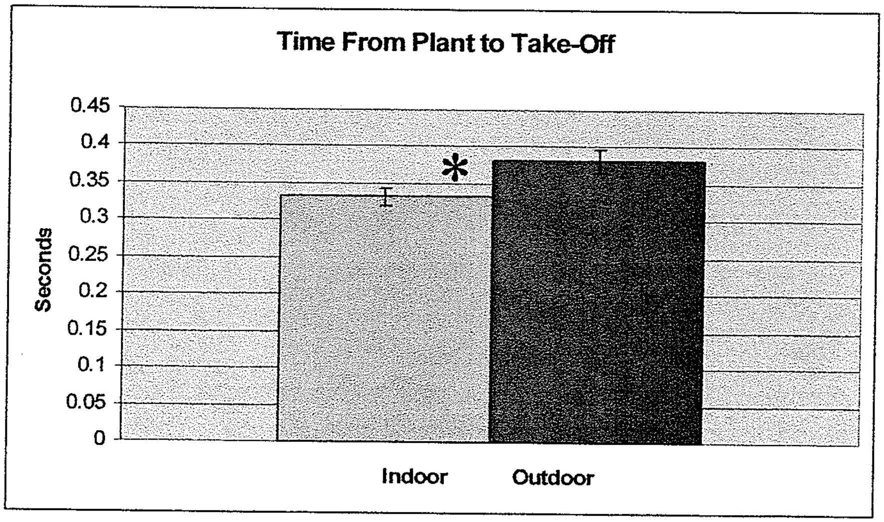


Figure 4.7: Mean time from plant to take-off between indoor and outdoor subjects showing significant difference in results.
(* p<.05).

Peak amounts of flexion were also measured in the hip, knee, and trunk joints as the athletes achieved the position of the deep crouch, or backswing of the jump. This phase is important as it largely determines the range of motion through which the athlete will be able to generate force during extension of the legs and trunk during force production and into take-off.

While no significant differences were found in the hip or knee angles, a significant difference was found in the angle of the trunk. Measuring the trunk angle to the vertical, the outdoor subjects showed a significantly greater amount of trunk flexion with a mean value of 27.22 degrees of flexion versus only 19.89 degrees of flexion in the indoor subjects (Figure 4.8).

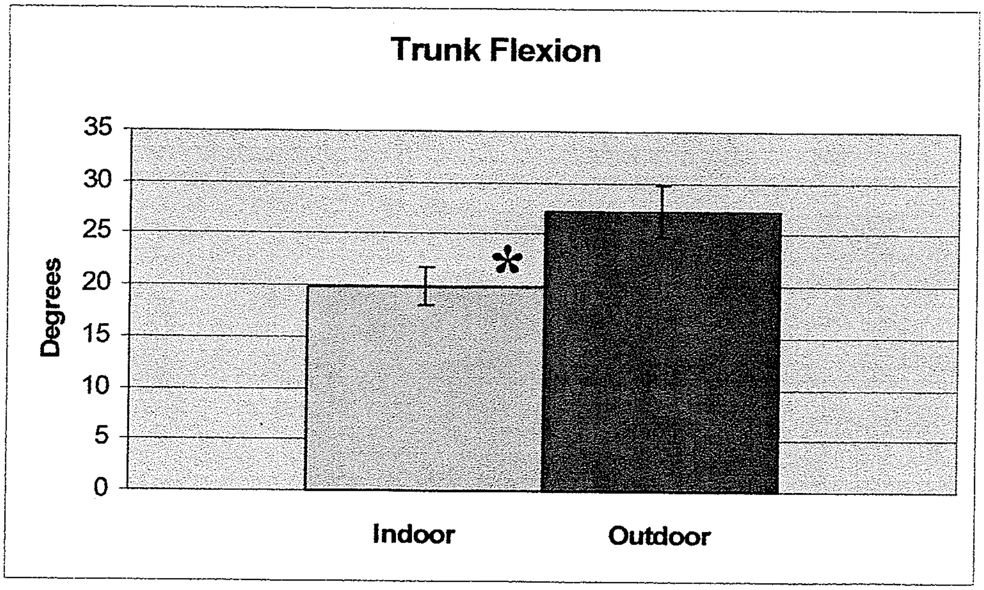


Figure 4.8: Mean trunk flexion during plant phase for indoor and outdoor subjects showing significant difference between groups.
(* p<.05).

Simultaneously, as the athlete reaches the deep crouch position, the arms swing forward by flexion of the shoulder joints. The peak angular velocity of the right shoulder was measured for all subjects and their group means compared. Despite a larger mean angular velocity of shoulder flexion of almost 100 degrees/second in the indoor subjects, this was not found to be a significant difference.

Take-off phase

The take-off phase of the volleyball spike is also referred to as the force producing phase of the jump. It begins following the plant phase when the athlete is in a position of maximum knee, and hip flexion (deep crouch) and involves all of the movements that occur up until the moment of take-off, or the instant that the athlete leaves the ground. A number of variables related to the production of force were measured in each subject (Table 4.4). These variables include: the angular displacement of the hip, knee, and trunk at the instant of take-off; peak angular velocities and the timing of their occurrence relative to the instant of take-off, of the hip, knee, and trunk; the vertical and horizontal velocity of the center of mass at take-off; and the height of the center of mass at take-off.

Standard t-tests between indoor and outdoor subject variables showed no significant difference in the angle of the hip, knee, or trunk at the instant of take-off. However, higher mean ranges of hip and trunk extension were found in the indoor subjects with lower amounts of knee extension.

Differences between the mean peak angular velocities at these joints were also not significant between groups. Indoor subjects recorded higher angular velocities during knee and trunk extension, but lower angular velocities at the knee joint. A large amount of variance was found in both groups making it difficult to isolate any significant differences amongst indoor and outdoor subject groups.

Table 4.4: Mean variables measured during the take-off phase of the volleyball spike for indoor and outdoor subjects.

Variables	**Indoor N=10**		**Outdoor N=10**		**p value**
	Mean	**SD**	**Mean**	**SD**	
Angular Displacements (deg)					
Hip	-17.31	9.39	-12.14	4.31	0.13
Knee	149.89	13.33	154.50	10.49	0.40
Trunk	-8.13	7.54	-5.92	2.86	0.40
Angular Velocities (deg/s)					
Hip	443.14	135.46	469.93	128.99	0.66
Knee	471.37	340.68	376.67	175.33	0.44
Trunk	156.86	64.36	139.75	93.91	0.94
Height of CM (Relative to Standing Height) (m)	1.14	0.05	1.06	0.05	0.001***
Horizontal Velocity (m/s)	1.68	0.58	0.92	0.19	0.01**
Vertical Velocity (m/s)	2.86	0.46	2.69	0.24	0.32

**p<.01; ***p<.001

One of the largest significant differences found between groups was measured and calculated for the horizontal velocity of the center of mass at take-off (as the athlete leaves the ground). Figure 4.9 illustrates the mean results for the horizontal velocity of the center of mass for the indoor and outdoor subjects. The indoor subjects demonstrated a mean horizontal velocity of 1.68 m/s while the outdoor subjects only possessed 0.92 m/s as a horizontal component of their resulting take-off velocity. The difference between the two means suggests that outdoor subjects attained much lower values of horizontal velocity at take-off than indoor subjects and this was found to be significant.

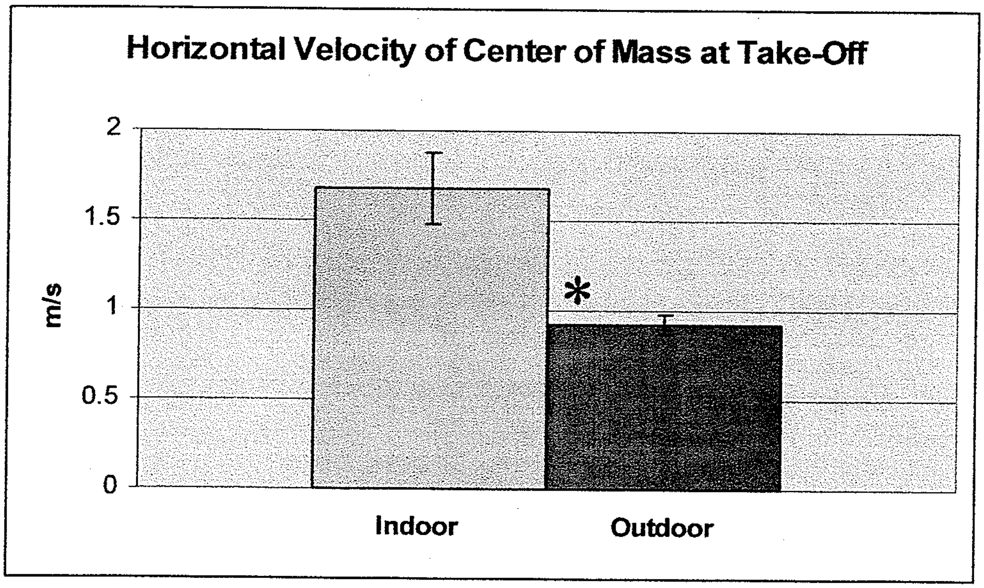


Figure 4.9: Indoor athletes demonstrate a significantly greater amount of horizontal velocity at take-off.
(* p<.001).

The last variable to be measured during the take-off phase was the mean height of the athletes' center of mass (measured from the ground up) at take-off. The position of the center of mass at take-off was calculated as a percentage of each athlete's body height. When the position of the center of mass at take-off relative to body height was compared between subjects, no significant difference was shown between indoor and outdoor subjects.

Figure 4.10 shows the change in horizontal velocity from plant to take-off for both the indoor and outdoor groups. This is equal to the change in momentum throughout the plant and take-off phases.

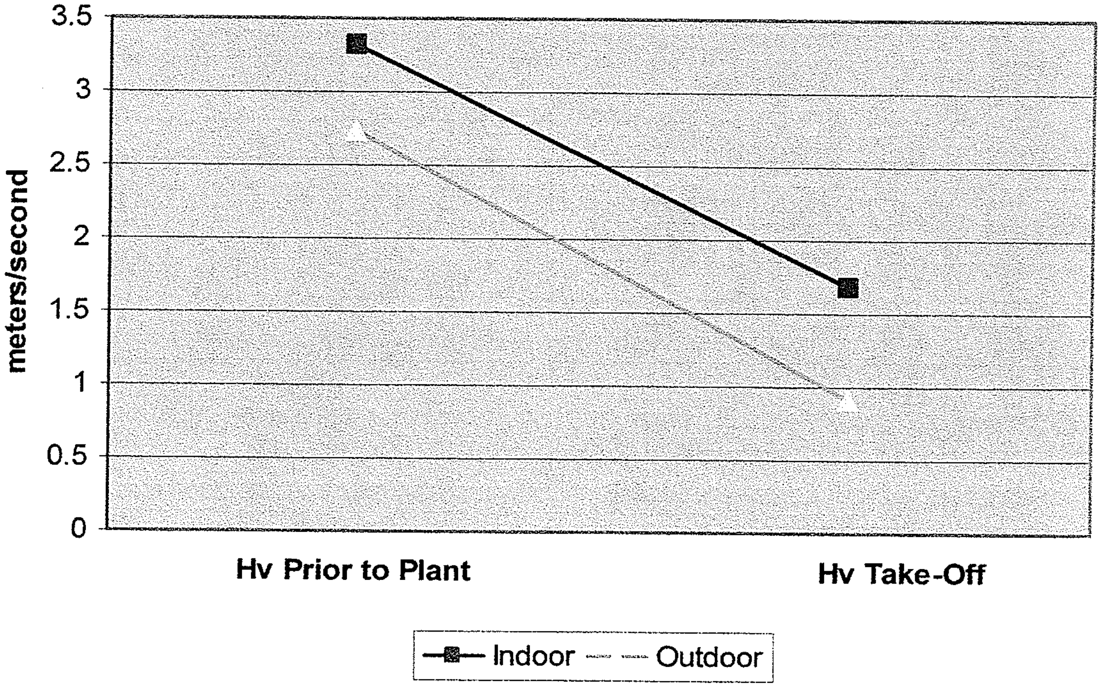


Figure 4.10: Change in horizontal velocity from plant to instant of take-off for both indoor and outdoor groups.

Airborne phase

The final phase of the indoor and outdoor spike approach that was analyzed was the airborne phase. This is the phase of the skill that occurs after the athlete leaves the ground and finishes after the player has made contact with the ball and lands from the jump. Only a few specific variables were measured during this phase, most of which have already been discussed in the beginning of this chapter. It should be mentioned again, that the purpose of this study was not to look at the movements that occur in the hitting action of the volleyball spike, but instead to investigate the mechanics of the jumping portion of the skill. Therefore, the only variables of concern included: the displacement of the center of mass from the instant of take-off to the peak height of the jump; the displacement of the right hip from take-off to peak height (used as a secondary measure for jump height performance after the displacement of the center of mass); the height of contact; and the distance of horizontal drift from take-off to landing. The first three of these variables have already been discussed and are shown in Table 4.1 and Figure 4.2. The final variable, the distance of horizontal drift was measured as the linear displacement of the left toe from the point where the left foot leaves the ground at take-off to where it lands at the end of the airborne phase. As shown in Figure 4.11, a significant difference in the amount of horizontal drift was observed between indoor and outdoor groups with indoor players showing a much larger amount of horizontal displacement than their outdoor counterparts. This was shown to be significantly different at the p<.002 level.

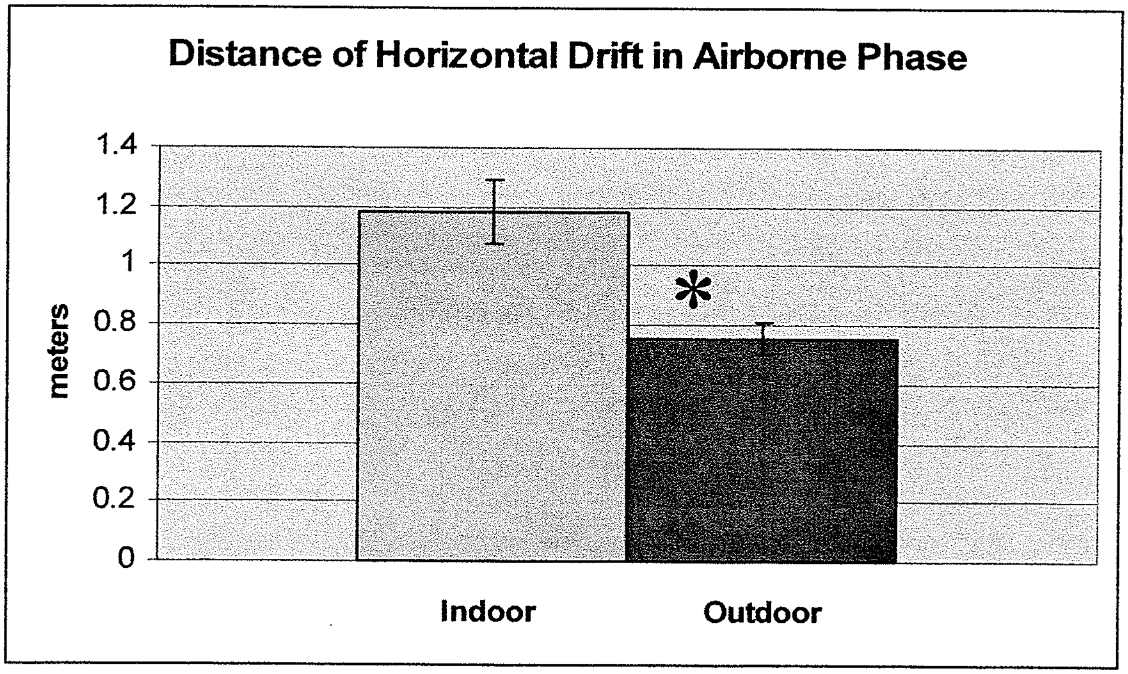


Figure 4.11: Comparison of the distance of horizontal drift in the airborne phase between indoor and outdoor subject groups. * p<.05.

Variable Effects on Jump Height

Indoor and Outdoor Conditions

In order to identify the factors that are responsible for the decrease in jump height attained in the outdoor spike approach, it was important to determine not only the differences between the indoor and outdoor spike approach, but also to determine which factors have the greatest impact on the outcome of jump height performance. In order to do so, indoor and outdoor groups were tested separately and each variable was analyzed using a Listwise Correlation test against the vertical displacement of the center of mass as a determinant of jump height performance. This was used to show any significant positive or negative relationships between the variables and their effect on jump height. Finally, a step-wise multiple regression test was also performed for both indoor and outdoor subjects separately in order to show which variables are the largest contributors to increasing jump height under each condition.

Table 4.5 shows a list of all indoor variables and the strength of their correlation with the vertical displacement of the center of mass (jump height). The variables a significant relationship to the vertical displacement of the center of mass were the vertical velocity of the center of mass at take off; peak trunk angular velocity during the take-off phase; step close time during the plant phase; and the total time from foot plant to take off. Other variables that also showed strong relationships with jump height included: the athletes' horizontal velocity prior to plant; the length of the last step; the position of the center of gravity in relation to the position of foot plant when the right foot plants after the last step; the amount of peak hip flexion in the plant phase; and the height of the center of mass at take-off (indicated by * in Table 4.5).

Table 4.5: Significant relationships of variables measured with the vertical displacement of the center of mass for indoor and outdoor groups. Relationships are indicated as either positive (+) or negative (-)

Variable	**Correlation**			
	Indoor N=10	**p value**	**Outdoor N=10**	**p value**
Approach Phase				
Horizontal velocity of CM prior to plant	+.526	0.12		
Length of last step	+.520	0.13		
Plant Phase				
Position of foot plant in relation to CM	+.650	0.04*		
Step close time	-.804	0.03*	-.518	+.129
Time from plant to take-off	-.802	0.003**		
Peak hip flexion	-.558	0.10		
Take Off Phase				
Vertical velocity of CM	+.795	0.004**	+.722	+.016*
Peak trunk angular velocity	+.745	0.01**		
Height of center of mass at take-off relative to standing body height	-.584	0.08		

*p<.05; **p<.01

The correlation analysis was performed on the data collected from outdoor subjects. Only one variable showed a significant relationship to jump height. Figure 4.12 plots the relationship between the vertical velocity of the center of mass and the vertical displacement of the center of mass. The only other variable shown to have a strong, but insignificant, negative relationship with jump performance was step close time (Figure 4.13).

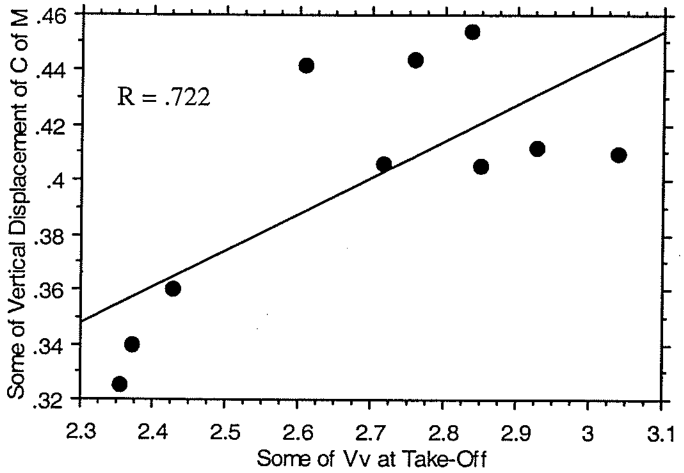


Figure 4.12: Relationship between vertical velocity of the center of mass at take off and the vertical displacement of the center of mass for outdoor group.
r=0.722; p<.05

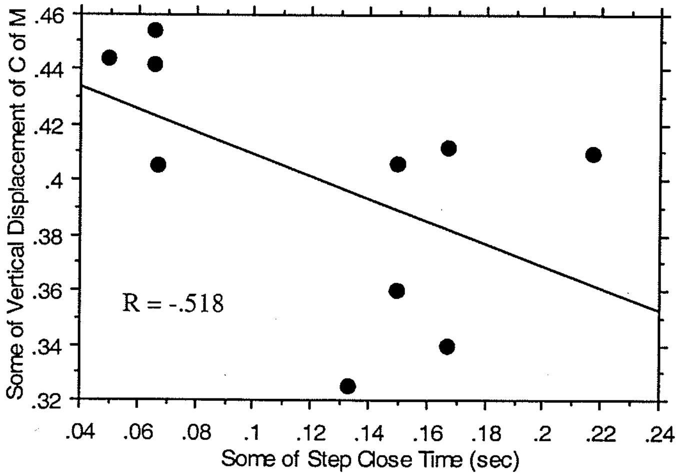


Figure 4.13: Relationship between step close time and the vertical displacement of the center of mass for outdoor group.
r=-0.518; insignificant

Some further comparisons were performed to show relationships between various variables. Figures 4.14a and 4.14b show the relationship between peak shoulder angular velocity as the arms are swung forward and upward during the plant and force-producing phases and maximum trunk angular velocity, which has been shown to be one of the key contributors to increasing jump height. The graph suggests that as the angular velocity generated by shoulder flexion increases, so does the angular velocity of trunk extension.

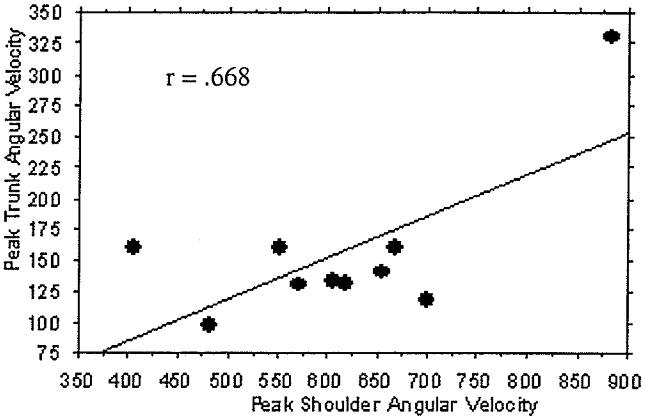


Figure 4.14a: Indoor subject group relationship between peak shoulder angular velocity and trunk angular velocity.
r=0.668; p<.05

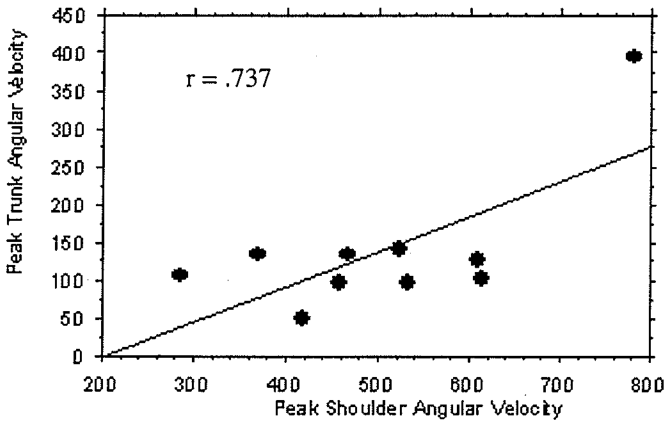


Figure 4.14b: Outdoor subject group relationship between peak shoulder angular velocity and trunk angular velocity
r=0.737; p<.05

Figure 4.15 shows a regression analysis involving the position of foot plant in relation to the position of the center of mass or how far in front of the athlete's center of mass she plants her foot and the horizontal velocity of the center of mass at take-off. For indoor subjects, as the foot is planted further in front of the line of gravity, the horizontal velocity of the athlete decreases. This however, is not shown to be true for outdoor subjects. No clear relationship is shown between the position of the center of mass relative to foot plant and the horizontal velocity of the center of mass at take-off for outdoor volleyball players.

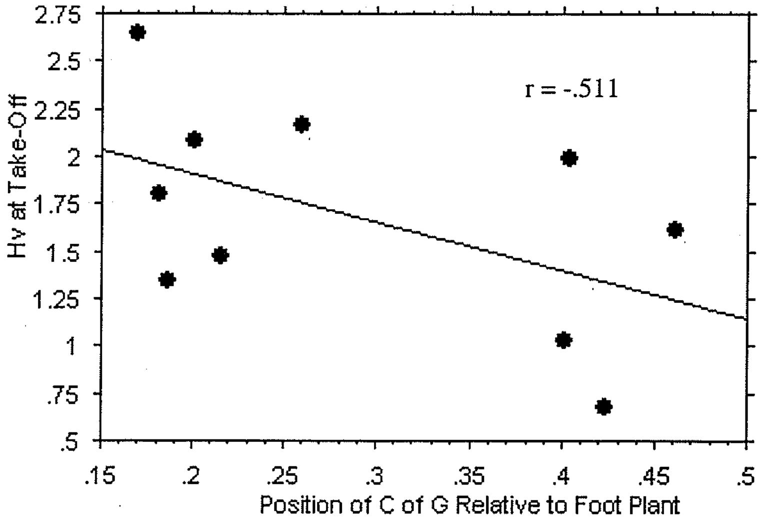


Figure 4.15: Indoor subject group relationship between the position of the center of gravity in relation to the position of foot plant and the horizontal velocity of the center of mass at take-off.
(r=-.511; p<.14 (not significant)

Furthermore, the indoor subject group showed that increases in the length of the last step were strongly correlated with an increase in the distance in front of the line of gravity that the foot is planted. Figure 4.16 shows a strong positive correlation of 0.796 (p<.004).

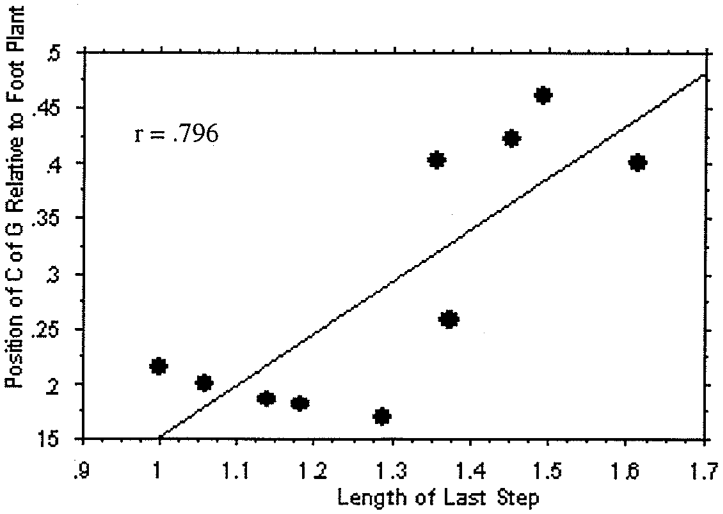
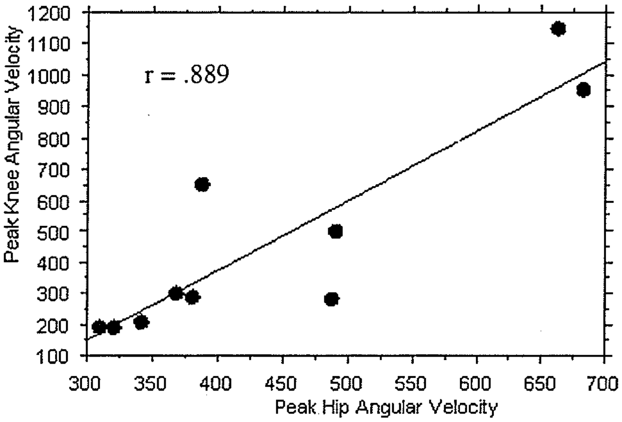


Figure 4.16: an indoor scatter plot showing a strong positive relationship between the length of the last step and the distance in front of the line of gravity that the foot plants.
(r=0.796; p<.004)



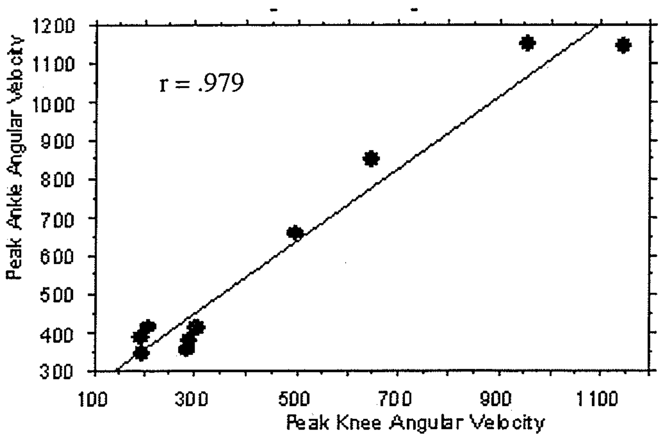


Figure 4.17a: an indoor group scatter plot showing a positive relationship between peak angular velocity of the hip and knee during take-off phase. (r=.889; p<.001)

Figure 4.17b: an indoor scatter plot a positive relationship between peak angular velocity of the knee and ankle during the take-off phase. (r=.979; p<.0001)

The final correlation focused on the segmental movements of the hip, knee, and ankle joints during take-off. Indoor subjects showed a strong positive relationship between the angular velocities of the hip, knee and ankle joints. Figure 4.17a shows that as the peak angular velocity of the hip joint increases so does the angular velocity of the knee joint and Figure 4.17b shows that as the angular velocity at the knee joint increases so does the angular velocity at the ankle joint.

In the outdoor condition, only the angular velocities of the hip and knee joints could be compared as ankle measurements could not be accurately made due to methodological problems. Figure 4.18 shows a strong positive relationship between the angular velocity of the hip and knee joints during the take-off phase.

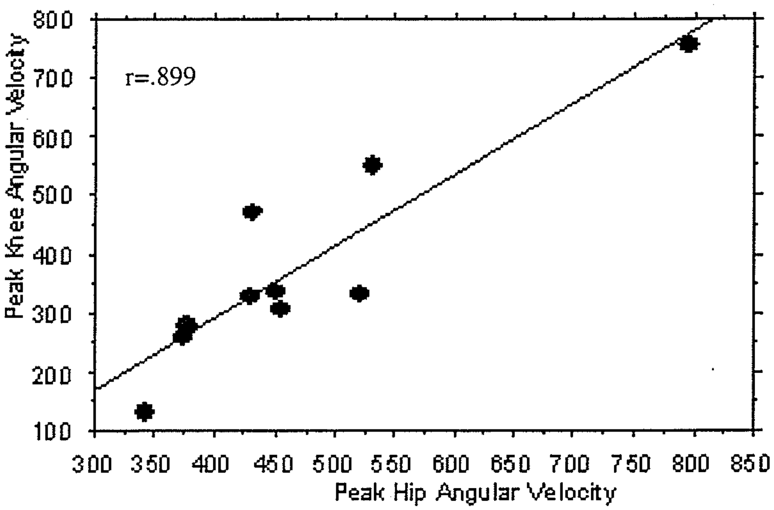


Figure 4.18: an outdoor scatter plot showing a positive relationship between peak angular velocity of the hip and knee during the take-off phase.
r=.899; p<.0001

Stepwise Regression Analysis

To conclude the statistical analysis of the study, two separate stepwise multiple regression tests were performed on all indoor and outdoor variables in order to determine the magnitude of each variable's effect on jump height performance.

Analysis of the indoor subjects identified eight variables to be the most important when trying to increase vertical jump performance. These eight variables identified by the stepwise regression analysis as the group of variables that together explain nearly all of the variance within the vertical displacement of the center of mass are listed in Table 4.6 and expressed in the following regression equation for the prediction of the dependent variable. Only five variables are included in the regression equation and account for 99.6% of the total variance in the vertical displacement of the center of mass.

Table 4.6: Summary table for a forward stepwise regression analysis of vertical displacement of the center of mass and 25 variables for the indoor subject group.

Variable N=10	**Coefficient**	**Std. Coeff.**	**F**	**P**
Length of Last Step	-.090	-.196	210.390	<.0001
Shoulder Hyper-Extension	-.001	-.322	91.240	<.0001
Position of CM Relative to Foot Plant	.032	.041	970288601.595	<.0001
Step Close Time	-3.100	-1.358	14.608	.0051
Peak Hip Flexion	-.005	-.302	41.189	.0002
Peak Ankle Dorsi Flexion	.016	.929	19.002	.0015
Peak Hip Angular Velocity	.000034	.00000004	26446.320	<.0001
Height of CM at Take-Off (Percentage of Body Height)	-.190	.-.071	852.906	<.0001

Regression Equation:

$$y = 1.5 - 3.1 * x_1 + 0.016 * x_2 - 0.005 * x_3 - 0.001 * x_4 - 0.09 * x_5$$

Where: y = vertical displacement of the center of mass (jump height)

x_1 = step close time (sec)

x_2 = peak ankle dorsi flexion (degrees)

x_3 = peak hip flexion (degrees)

x_4 = peak shoulder hyper extension (degrees)

x_5 = length of last step (m)

In the outdoor spike condition, only 23 variables were included in the stepwise regression analysis. Two less variables were used than in the indoor group analysis due to the removal of ankle displacements and velocities from the data set because of difficulty identifying and digitizing the positions of the points that make up the foot segment. The results of the stepwise regression show only two variables to have a large enough effect on the vertical displacement of the center of mass to be included in the regression equation. These variables, as shown in Table 4.7, were the vertical velocity of the center of mass at take-off and the duration of the step-close during the plant phase. From the data provided by the stepwise regression analysis of the outdoor subject group no regression equation could be derived.

Table 4.7: Forward stepwise regression analysis of the vertical displacement of the center of mass and 23 related independent variables for the outdoor subject group.

Variable N=10	**Coefficient**	**Std. Coeff.**	**F**	**P**
Vertical velocity at take-off	.135	.731	8.704	0.184*
Step close time	-4.14	-.531	14.309	.0034**

* $p<.05$; **$p<.01$

CHAPTER 5

DISCUSSION

The skills involved in the sport of beach volleyball are similar to those of the more popular indoor game. However, it would not be correct to assume that they are optimally performed using the same mechanics that indoor players have used in the indoor game. With beach volleyball being played on a sand surface 40 centimeters in depth, the dynamic movements that an athlete has to make during competition, whether it be changing direction, diving to dig a ball, blocking, or in this case approaching and jumping to spike a volleyball, will be very different due to how the sand reacts to the forces applied on it by the feet. The purpose of this study was to determine the kinematic differences in the volleyball spike approach and take-off between indoor and outdoor elite competitors and the factors most responsible for a decrease in jump height in the outdoor condition. This information could then be used to improve the understanding of the mechanics involved in spiking in beach volleyball and assist coaches and athletes with the development of the skill.

It is important to explain that the focus of this study was to explore the biomechanics of the approach and take-off of the spike only. Although the airborne movements occurring in the hitting action of the arm are also critical to performing a successful spike, they were not included in this study. Jump height was used as the key determinant for jump performance because a higher jump height provides the opportunity for a better outcome of the spike. A higher vertical jump will increase the height at which contact occurs providing advantages to the hitter by helping to avoid blockers and increasing the area of the court into which the ball can be hit. A higher vertical jump will also increase the attacker's time in the air and increase the amount of time over which the segmental movements involved in the hitting action can occur. Allowing more time for the airborne movements to take place provides for a larger range of motion at the trunk, hitting shoulder, and lower body. This increases a volleyball player's potential for a higher and more forceful contact on the ball. The hitting actions occurring during the airborne portion of the spike have been widely studied (Oka, Okamoto, Kumamoto, 1975; Maxwell, 1982; Chung, Shin, Choi, 1990; Wedaman, Cynthia, Wilkerson, 1990; Coleman et al., 1993) and are understood to be of importance to the outcome of a spike, however the approach, take-off and a high vertical jump are predecessors to the actions occurring in the air and provide the backbone of the spike action to follow.

This study examined the approach, plant, take-off, and airborne phases of the volleyball spike as performed on both the indoor hardwood court surface and the outdoor sand surface. Several variables were measured using video analysis and the Peak 5 Analysis software (Peak Performance Technologies, 1994). Each of these variables were subjected to statistical analysis in order to first determine any mechanical differences that existed between the indoor and outdoor subjects, and then to identify those variables most related to jump height performance. Jump height performance was determined by measuring the vertical displacement of the center of mass from the instant of take-off to the point of peak height. This vertical displacement was used as the outcome measure of performance. A greater vertical displacement indicated a higher jump and therefore a better performance. Tests to determine which variables showed the strongest relationships with jump height performance were performed on the spike data from indoor and outdoor subject groups. This was to determine which variables had the greatest relationship with the vertical displacement of the center of mass. This information was used to determine which variables were of the most importance to the athlete and coach in performance of a spike approach and take off in the indoor and outdoor conditions.

Prior to any data collection, all outdoor subjects were also interviewed in order to determine what they thought the most significant differences were, if any, between the outdoor and indoor spike approach and take-off.

Subject Interviews

Ten subjects from the outdoor group were asked to express the differences they experience when performing the outdoor spike approach and take-off in the sand versus the traditional spike skill of the indoor game on the hardwood floor. Eight different responses were gathered from the opinions of the subjects. Nine subjects suggested that they use shorter steps or a shorter approach in the outdoor game, eight subjects said in the outdoor game, the spike jump is closer to straight up as opposed to the horizontal drift seen in the indoor spike jump. A slower approach or a difference in timing due to the observation of other factors such as the wind, and the opposing team's defense was suggested by three subjects and one subject contradicted this by reporting that she felt the outdoor approach was faster with smaller steps to prevent the feet from sinking into the sand. Three subjects also indicated that they use a greater arm swing to help jump, two subjects said that they need to get the arms up early to prepare to adjust to hitting the ball and one subject said that she used her body more to help jump, while another felt she got lower in the knees during the plant.

Several variables affecting the height of the jump were mentioned by the outdoor subjects showing their awareness of some of the key differences between the indoor and outdoor spikes. However, some other comments are not supported by this study and indicate that some beach volleyball competitors may be unaware of the key differences between the indoor and the outdoor spike approach and take-off technique.

Vertical Displacement of the Center of Mass

The center of mass for each subject was calculated by the Peak 5 software using the segmental method and was then tracked throughout the entire spike (Peak Performance Technologies, 1994). The height of the center of mass in the y-direction at take off was subtracted from the peak height that the center of mass reached at the highest point of the jump in order to calculate the vertical displacement of the center of mass. This value was used as the key measure of performance in the vertical jump. The greater the vertical displacement of the center of mass, the higher the athlete jumped, and with the goal of this study to improve jumping ability in the sport of beach volleyball it seemed reasonable to use jump height as the outcome measure of performance.

When the vertical displacement of the center of mass was measured for ten elite indoor and ten other elite outdoor volleyball players and their mean values compared, a significant difference in jump height between groups was found. A 12.7 percent difference in performance, measured as lower jump height, was found for outdoor athletes. This is in agreement with the hypothesis of this study that outdoor players would show a decrease in jump height. However, the scope of this study was to determine whether or not the decrease in jump height was the result of biomechanical technique differences found between groups or solely the result of the sand surface. Biomechanical variables affecting jump height were measured and compared between groups in order to identify any differences that exist which may inhibit the jumping ability of outdoor volleyball players. These variables have been divided into the four phases of the volleyball spike; the approach; the plant; the take-off; and the airborne phase.

Approach phase

During the approach phase, all subjects began their approach with a step onto their left foot (Figure 5.1). This first step is used as a directional step in order to adjust to the path of the set and where the ball will be contacted on the spike. The player must approach, plant and jump straight up so that the hand can meet the ball in an optimal position and height. Various game situations will require players to make different adjustments in the approach in order to accommodate to the speed and trajectory of the ball after it is set. These adjustments can also be affected by the player's position on the court relative to where he or she must make contact with the ball when hitting. This

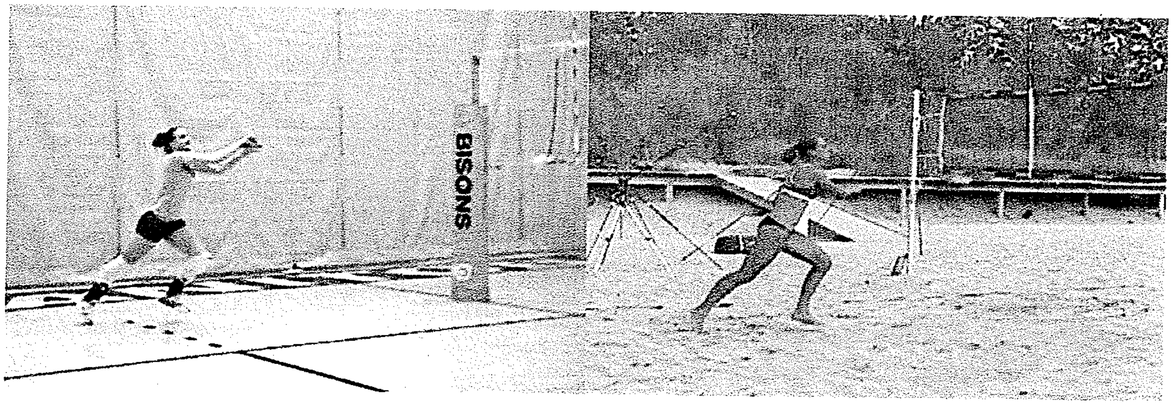


Figure 5.1: First step shown as directional step for indoor and outdoor conditions.

positioning becomes more demanding in the sport of beach volleyball where only two players must cover the entire court. As a result, a player may pass the ball from deep in the court and then take several steps in order to get in position to approach and jump to spike the ball or the player may dig a short ball, very shallow in the court, and only have a short time and small distance to go to spike the ball. In either condition, the optimal technique for the spike approach does not change. Whether the player runs six steps forward or backs up two steps, she needs to get into a position from which the same directional step onto the left foot can begin the final portion of the spike approach. In indoor volleyball, the athlete rarely has to cover the same large area of the court and as a result the spiking condition is more controlled and allows the athlete to begin the approach from the same position with the same footwork each time.

After the left foot is planted, the athlete begins to increase her horizontal velocity by pushing off the back (left) foot, driving the opposite knee and foot forward while the arms begin to hyperextend behind the body. This final step of the spike approach should be the longest allowing the right foot to be planted well in front of the line of gravity. A significant difference in the horizontal velocity of the center of mass prior to the right foot plant was found between indoor and outdoor subjects. In this study, indoor subjects produced a horizontal velocity of 3.32 m/s versus only 2.74 m/s for outdoor subjects. This is a 17.5 percent difference in the horizontal velocity of the approach for the outdoor condition. Increasing horizontal velocity throughout the approach is important leading into the plant phase so that when the foot plants well in front of the body, the horizontal forces on the foot will not only slow the athlete down, but will force the lower body into greater hip and knee flexion. This increased flexion at the knee and hip in combination with an increased stiffness in the joints due to a forceful eccentric contraction of the hip and knee extensors results in an increased tension in the muscles crossing these joints and therefore a more forceful prestretch which initiates the stretch reflex (Dapena, 1988). The stretch reflex is a concentric contraction that is activated by the forceful prestretch of that same muscle. The magnitude of the contraction is dependent on the rate at which the muscle is stretched. The faster the muscle is stretched or lengthened, the faster a contraction will occur, and the greater the concentric force output will be (Chu, 1998). A more forceful prestretch of the muscle will create a greater amount of stored elastic energy in the series and parallel elastic component of the muscle that can subsequently be released to increase the force of the concentric contraction of the same stretched muscles as they shorten to drive the athlete up through the take-off phase of the jump.

Outdoor subjects exhibited a slower horizontal velocity as they entered the plant phase. The slower approach may be partly related to the increased difficulty of moving the feet through the deep sand surface but, as will be explained later, it is most likely a biomechanical adaptation to the approach in order to improve performance on the sand surface. With a slower approach, the magnitude of the braking force that the ground applies on the foot is decreased and the athlete is not forced into the same amounts of knee or hip flexion or the same forceful eccentric contraction that the indoor subject experiences.

The length of the last step was also measured as the linear distance from the left toe as it pushes off the ground to the position where the right toe contacts the ground to begin the plant phase (Figure 5.2). Figure 4.4 illustrated the significant difference in the length of the last step between groups. The indoor group of subjects produced a step length of 1.30 meters while the outdoor group had a significantly shorter last step of 0.99 meters. This 0.3 meter difference in step length can be explained as a result of the slower horizontal velocity produced by outdoor players and the reaction of the sand to foot plant and its ability to apply braking forces back on the foot. The purpose of the long last step is to increase the distance that the foot is planted in front of the line of gravity. The further in front of the line of gravity that the foot is planted, the greater the horizontal component of the ground reaction force and the more effectively horizontal velocity can be decreased. As well, the stretch reflex is elicited from stretching the extensors. Figures 5.3(a) and 5.3(b) illustrate the component forces acting on the foot in the indoor and outdoor condition respectively and how they change depending on the angle at which the foot approaches the plant. The angle that the foot approaches the plant is shown as the path of the heel of the right foot prior to contact with the ground.

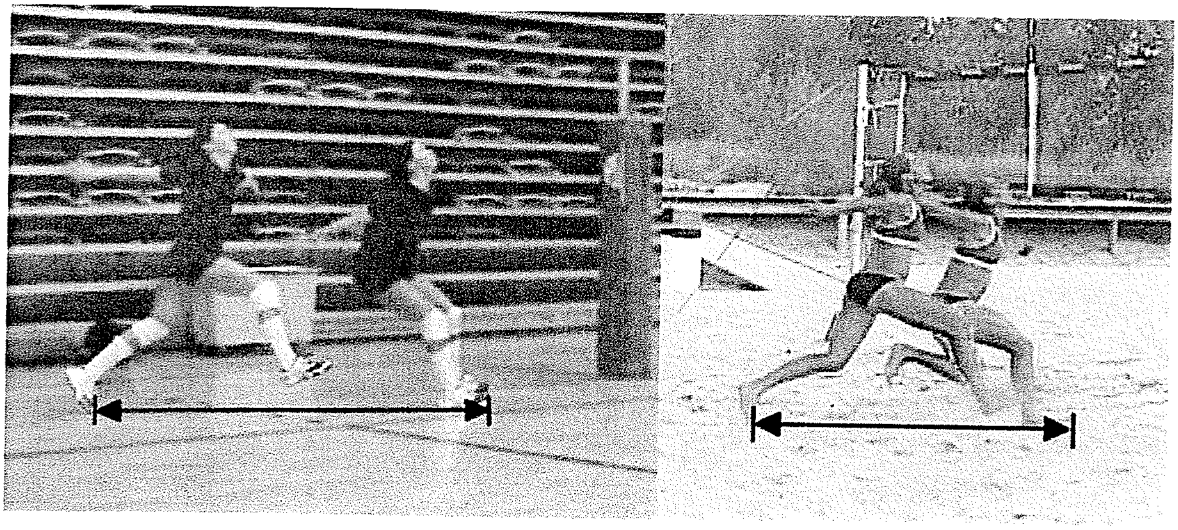


Figure 5.2: Length of last step during the approach phase. Indoor subjects showed a significantly longer last step (p<.05).

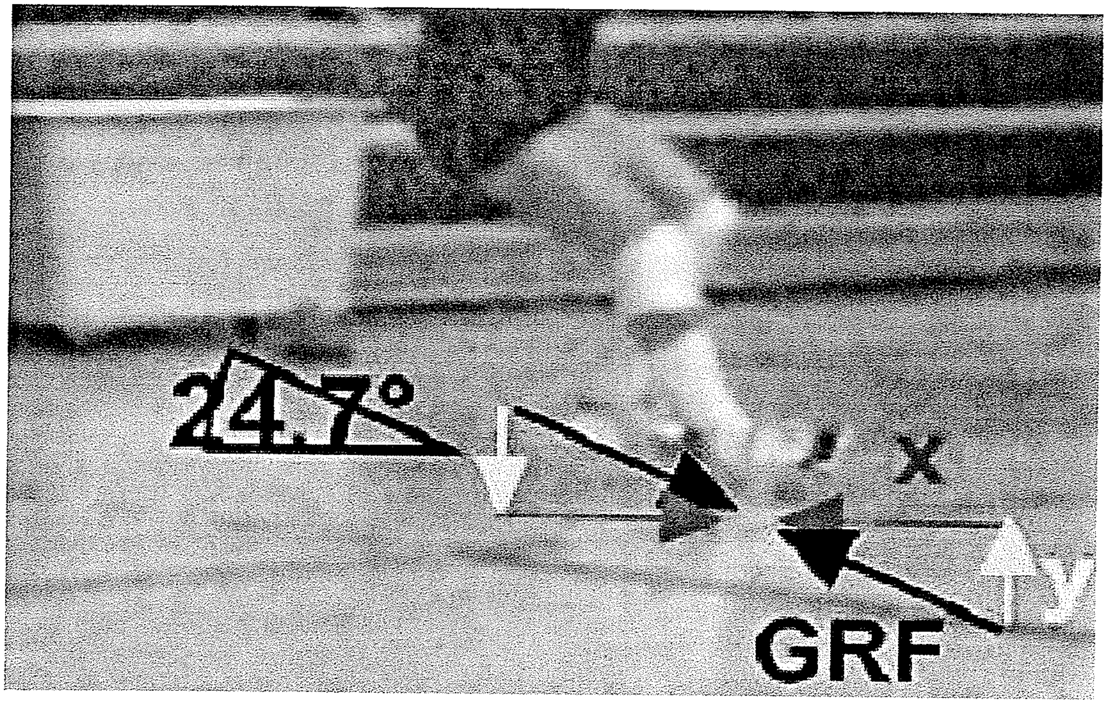


Figure 5.3 (a): Model of ground reaction forces (GRF) shown acting on the foot of an indoor player at plant. Horizontal component of GRF is labeled as x and is larger (indicated by longer arrow) when the foot is planted further in front of the line of gravity at a smaller angle to the ground.

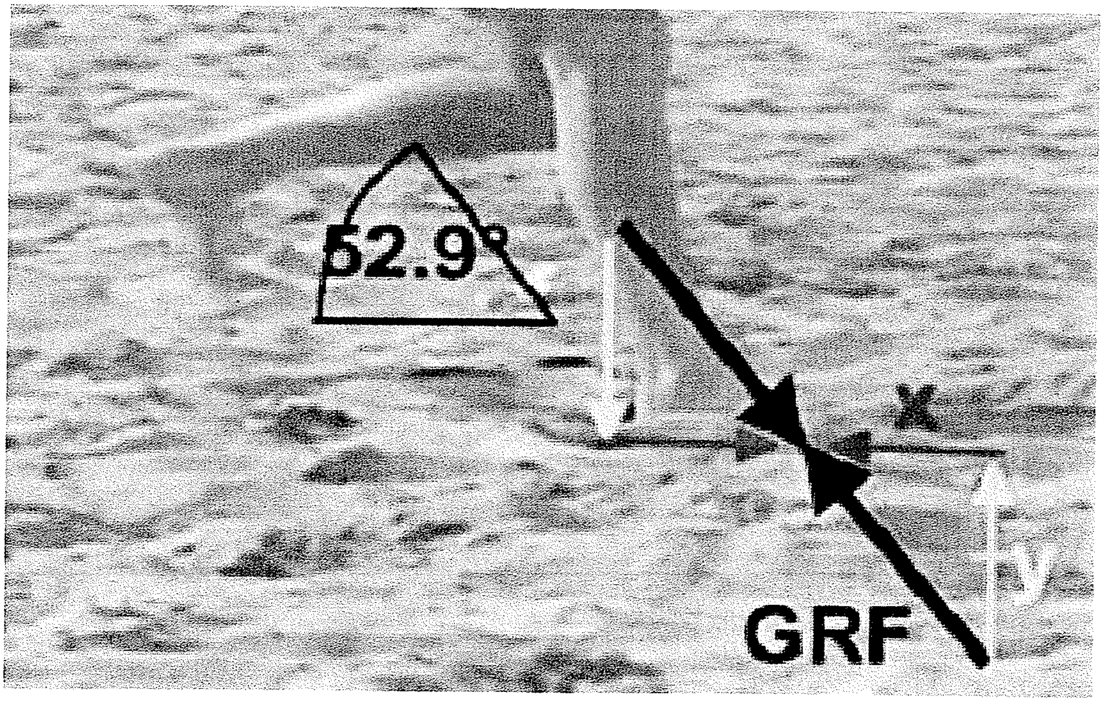


Figure 5.3 (b): Model GRF acting on the foot of an outdoor player. Foot is planted closer to the midline at a steeper angle to the horizontal resulting in a smaller x component of the GRF than in Figure 5.3 (a).

Outdoor subjects enter the plant phase with a slower horizontal velocity and therefore less horizontal momentum (momentum = mass x velocity). With less momentum to begin with, smaller ground reaction forces in the x-direction (braking forces) are required to slow the athlete down sufficiently to prepare for the take-off phase. This suggests that the athlete with a slower horizontal velocity earlier in the approach does not require the same long last step as the indoor athlete.

If the outdoor athlete were to use an approach similar to the indoor volleyball player, with a faster horizontal velocity and longer last step, the sand surface would not have the rigidity to apply a large enough impulse to the foot to decrease horizontal momentum as effectively as the hardwood floor and rubber soled shoes of the indoor court does. Impulse is equal to the change in momentum of the athlete and is the product of force and time. In outdoor volleyball, when the foot plants into the softer sand surface, the sand reacts much differently than the hardwood floor. Some of the sand is displaced (pushed forward by the foot) and a portion of the athlete's forward momentum is taken up by the displacement of the sand, then the time required to sufficiently decrease momentum would be much longer. The force of the sand pushing back on the foot would be much smaller because impulse is equal to the product of force times time and impulse produces the change in momentum. As the length of time that it takes to change momentum increases, the amount of force applied decreases and in this case, less force pushing back on the athlete results in a less forceful eccentric contraction in the hip and knee extensor muscles and a less effective stretch reflex.

Plant phase

The plant phase of the spike approach begins immediately when the right foot (for right handed players) contacts the ground after the long last step and consists of all the backswing movements of the jump. The backswing phase of a skill consists of all body movements away from the direction of force production. This is the most critical phase of a skill as it prepares the body for force production by placing it in the most effective position possible. The purpose of the backswing is to elicit the stretch reflex by placing the force producing muscles on a pre-stretch and to maximize the range of motion or length of time over which force production can occur. An effective backswing will provide the opportunity for an effective force producing phase and critical instant. The backswing movements occurring during the plant phase include the initial foot plant; the second foot plant; the timing between the two of them (step-close time); hip, knee, trunk flexion, and ankle dorsi flexion; shoulder angular velocity as the arms swing down past the body (flexion) and begin upward through shoulder flexion; and the total time of ground contact from plant to take-off. Figure 5.4a and 5.4b illustrate the movements occurring during the plant phase of an outdoor and indoor volleyball spike respectively.

The timing between the right and left foot plants is referred to as the step-close time. Before the right foot plants during the last step of the approach, the left hip flexes bringing the left foot, the trailing foot, forward closer to the front foot. This way, the left foot can plant (second foot plant) immediately after the right foot (initial foot plant). All indoor subjects in this study demonstrated a “fast step-close technique” where the trailing foot plants immediately after the front foot. Coutts (1978) classifies the step close into three categories: the hop; slow step close; and fast step close. The focus of Coutts’ study

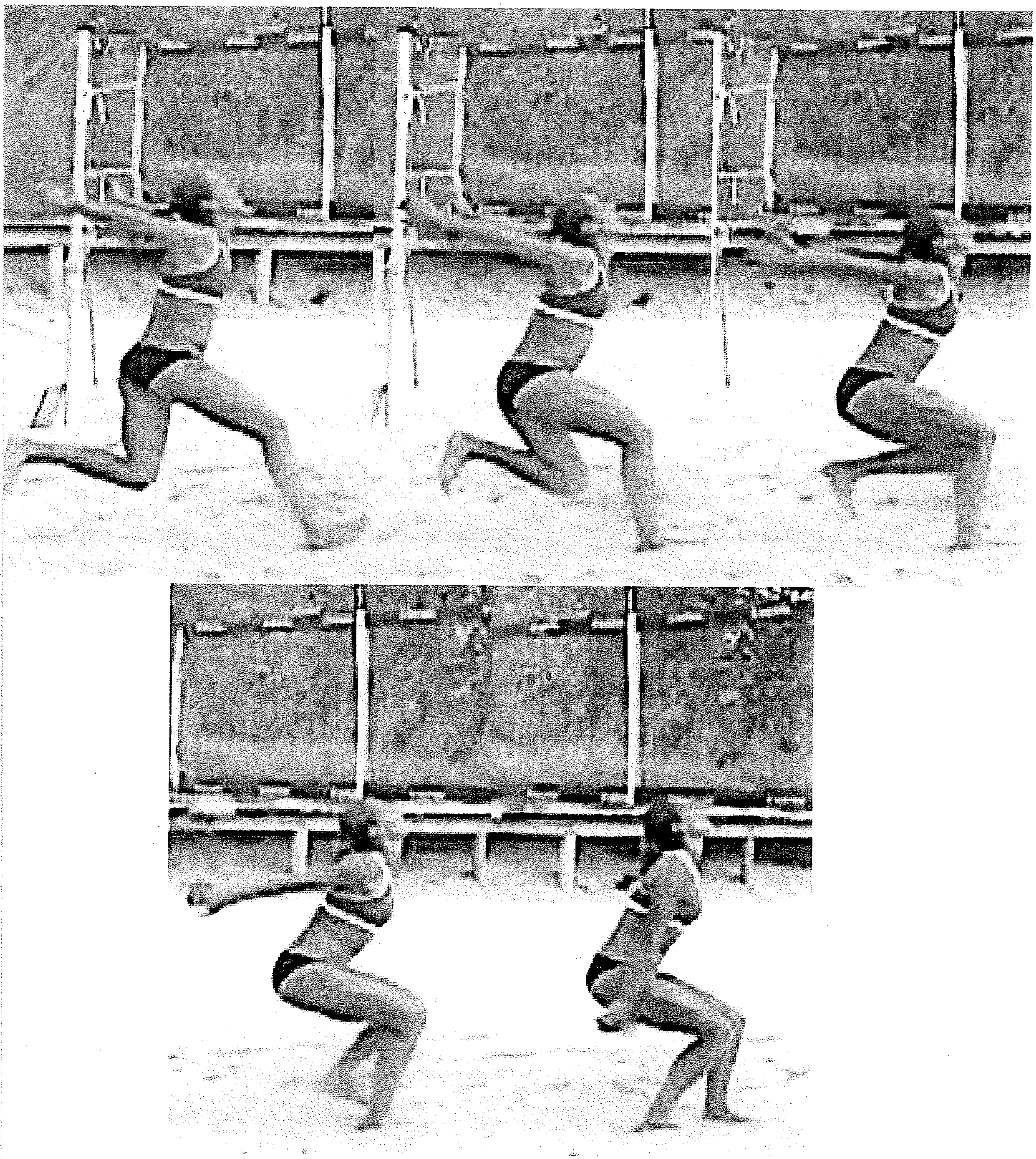


Figure 5.4a: Plant phase (backswing) of an outdoor volleyball spike.

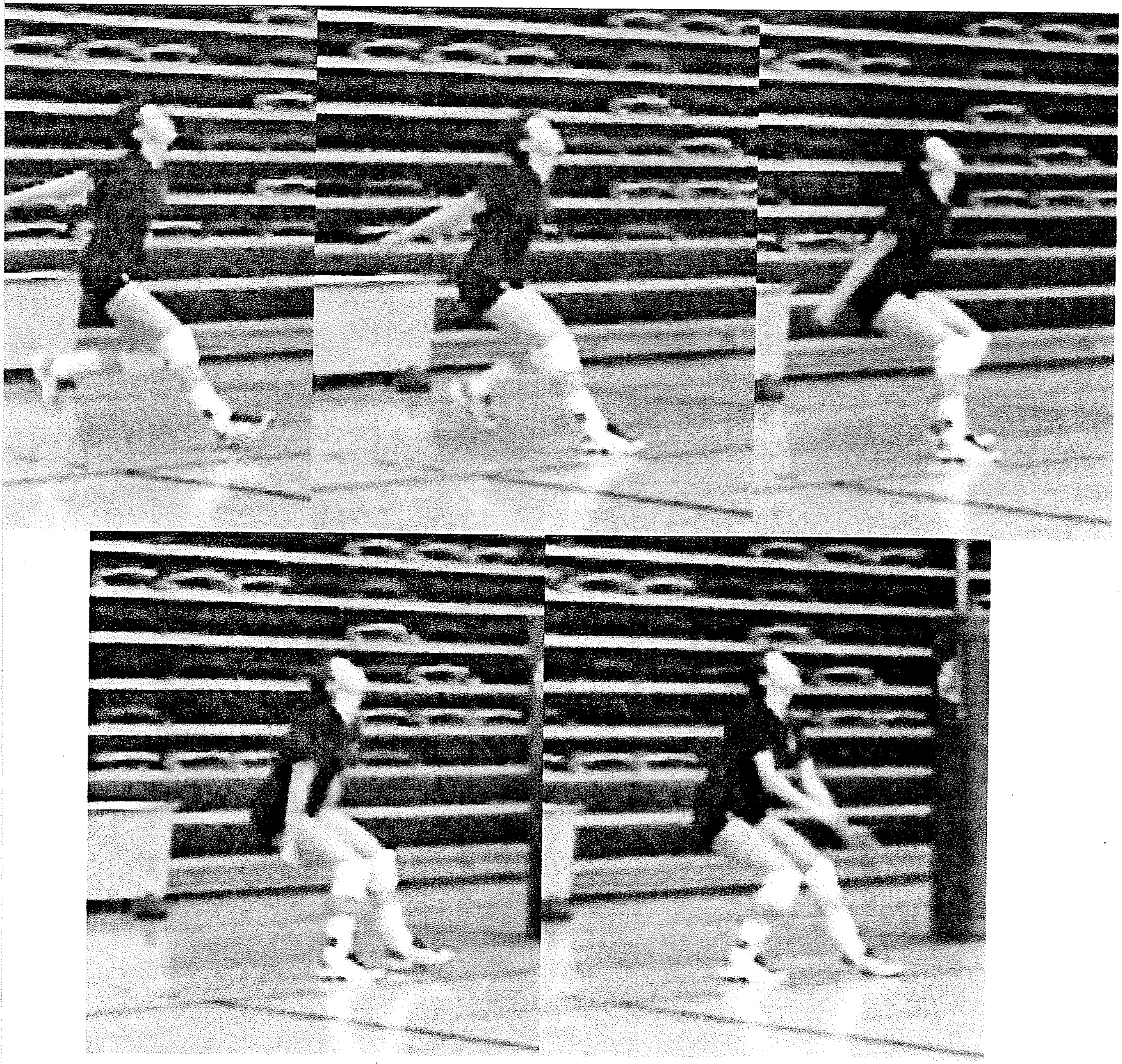


Figure 5.4b: Plant phase (backswing) of an indoor volleyball spike.

was to measure the total force impulse from plant to take off for the spike under each of the three types of plant. In his study, step close time was not measured between foot plants; however the time over which the impulse was applied from plant to take off was measured. His results showed that a fast step close spread the force over 0.33 seconds from initial foot plant to take off. This is identical to the mean values of the indoor subject group for the total time from plant to take off, also calculated as 0.33 seconds. On the other hand, the outdoor subject group showed a mean time from plant to take-off of 0.38 seconds which is closer to a slow step close as categorized by Coutts who classifies a slow step close as one taking 0.46 seconds. It is important to note that outdoor subjects showed a shorter time lapse between right and left foot plants by a mean difference of 0.06 seconds. This suggests that the step close itself should still be classified as a "fast step close" and that the longer total duration of time from plant to take off must be the result of other factors occurring after the feet plant.

The shorter the time delay is between foot plants, the faster the braking phase will be and the higher the peak absorption forces are on the muscles, tendons, and ligaments of the lower body. Referring back to the impulse-momentum relationship, for an athlete to decrease her horizontal momentum during the plant, an impulse must be applied as some force over a period of time. If impulse is equal to the change in momentum and to the product of force times time, then a faster impulse, created by a faster step-close, must result in higher forces applied through the feet and legs in order to change momentum. This is supported by a study by Coutts (1978) which measured peak absorption forces for the three different types of plant. The hop technique, with the shortest ground contact time showed the highest peak absorption forces of five times the player's body weight, while the fast and slow step close techniques demonstrated a peak absorption force of 3.7 and 2.8 times body weight respectively.

Two sample calculations have been made to illustrate how peak absorption forces are affected by a fast versus a slow step close time. The data used in these calculations were collected from one indoor subject with a faster step close and one outdoor subject with a slower step close. Peak absorption forces were calculated by determining the horizontal momentum of the athlete as she entered the plant and the horizontal momentum at take-off. This information was used to determine the amount of impulse applied to cause a change in momentum and knowing impulse and the time over which it was applied (time from plant to take-off) the force necessary to produce the impulse over that given period of time could be calculated. The fast step close was found to generate peak absorption forces of 329.79 newtons or 4.84 times the athlete's body weight. On the other hand, a slower step close is consistent with a slower approach with less horizontal momentum to begin with and therefore less horizontal momentum to decrease. As a

	Fast Step Close:	**Slower Step Close:**
1	Momentum$_{plant}$ = mass x Hv$_{plant}$ Momentum$_{plant}$ = (68.18kg) x (3.68m/s) Momentum$_{plant}$ = 250.90 kgm/s	Momentum$_{plant}$ = mass x Hv$_{plant}$ Momentum$_{plant}$ = (58.18kg) x (2.845m/s) Momentum$_{plant}$ = 165.52 kgm/s
2	Momentum$_{TO}$ = mass x Hv$_{TO}$ Momentum$_{TO}$ = (68.18kg) x (1.987m/s) Momentum$_{TO}$ = 135.47 kgm/s	Momentum$_{TO}$ = mass x Hv$_{TO}$ Momentum$_{TO}$ = (58.18kg) x (1.095m/s) Momentum$_{TO}$ = 63.71 kgm/s
3	Impulse = change in momentum Impulse = 250.9kgm/s – 135.47kgm/s Impulse = 115.43 Ns	Impulse = change in momentum Impulse = 165.52kgm/s – 63.71kgm/s Impulse = 101.81 Ns
4	Force = Impulse/Time Force = 115.43 Ns/0.35s Force = 329.79 Newtons	Force = Impulse/Time Force = 101.81 Ns/0.45s Force = 226.24 Newtons
	329.79N/BW = **4.84 x BW**	226.24/BW = **3.9 x BW**

result the impulse applied to decrease horizontal momentum was 13.62Ns lower. A slower step close also spreads the impulse over a greater duration requiring less peak absorption force to be applied to the body over a longer period of time. This was the case in the calculation of peak absorption forces for a slower step close as they were found to be only 3.9 times body weight for the outdoor subject used in the example.

The greater the amount of force that is applied back on the athlete, the more the tension in the muscle is increased by the passive stretch of the muscle tissues. This stretch occurs as the knee and hip joints are forced into greater flexion creating a greater eccentric contraction of the knee and hip extensors as they attempt to shorten but continue to lengthen under tension as an impulse is applied. This results in a more effective stretch reflex with more elastic energy generated in the series and parallel elastic components of the muscle. Figure 5.5a demonstrates an athlete from the outdoor subject group performing a fast step-close technique with a step-close time of 0.15 seconds and a total time from plant to take off of 0.37 seconds. Figure 5.5b shows an indoor subject performing the same plant phase with the same key positions captured. This subject demonstrates a step close time of 0.18 seconds and a total ground contact time of 0.35 seconds.

Although both the indoor and outdoor groups demonstrated a fast step-close technique there was a significant difference in the duration of the step-close. Indoor subjects showed a slower step-close of 0.18 seconds versus 0.12 seconds for outdoor players. This would suggest that outdoor subjects endure greater peak absorption forces; however this is not the case. As mentioned earlier, when outdoor subjects plant their feet the sand is displaced and it absorbs some of the athlete's momentum in the same

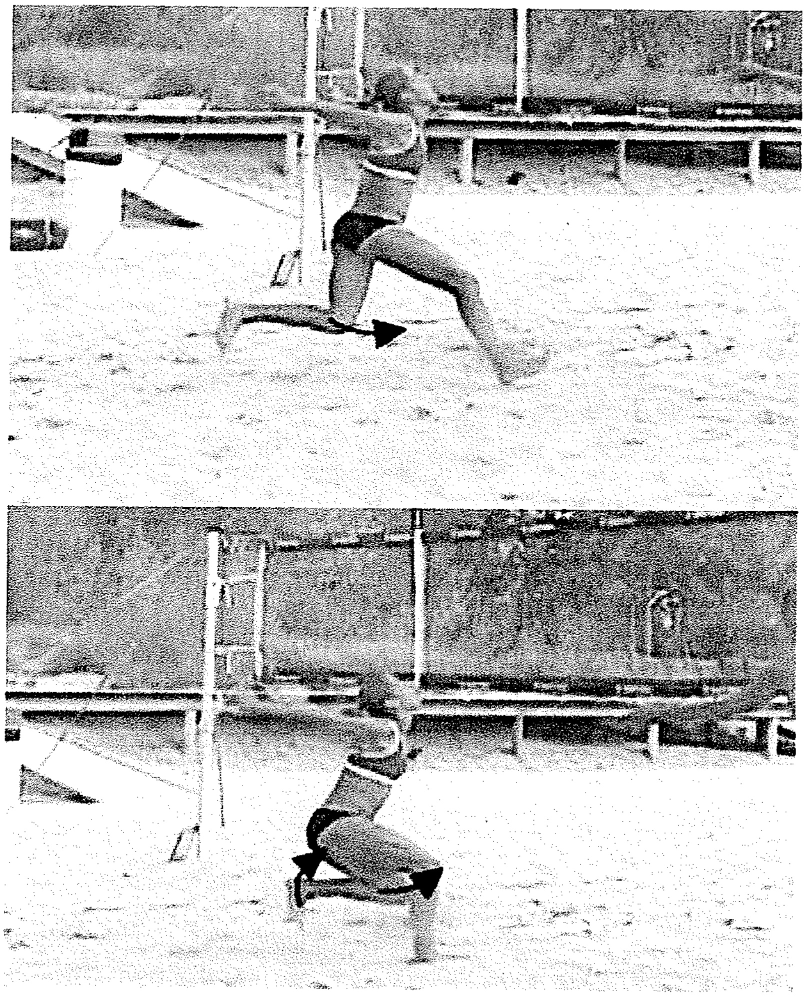


Figure 5.5a: Characteristic of the fast step-close technique is flexion of the hip and knee of the trail leg during the last step. This enables the trail leg to plant 0.15 seconds after the initial foot plant.

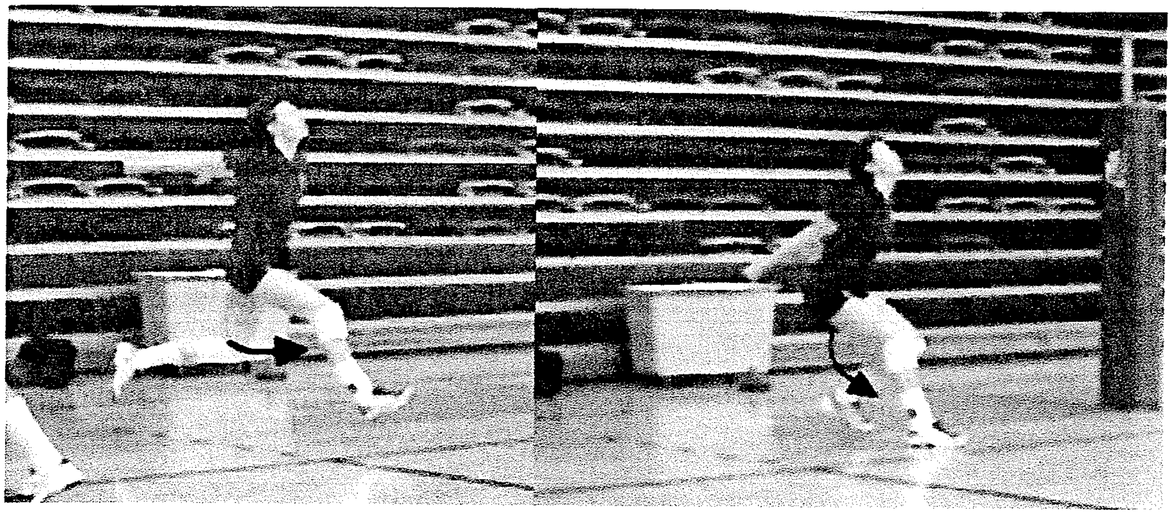


Figure 5.5b: Fast step-close technique as seen in the indoor subject group. Step close is slower (0.18 sec) than that of the outdoor subject in Figure 5.5a. Note less flexion at the knee and hip of the trailing leg.

direction that the athlete is moving. As a result less force is applied back on the athlete by the sand because the change in momentum requires a greater amount of time.

A faster step-close may be used in beach volleyball to reduce the amount of time spent on one foot. Planting both feet quickly increases balance on an unstable surface by increasing the surface area of the base of support. As well, Coutts (1978) referred to the second foot plant as a final tap on the brakes before the main extension effort is initiated. Therefore, if the initial foot plant is ineffective in slowing the horizontal velocity of the athlete, the second foot plant becomes more important to make a second, and final, effort to decrease horizontal velocity. When the first foot plants in the sand surface its first movement will be to displace the sand and slide forward. This instant inability to slow down the athlete and maintain balance may force the trailing foot to plant quicker, helping to slow down the athlete, control horizontal velocity and maintain balance.

To further explain the difference in impulse generated between indoor and outdoor groups, the total duration of ground contact time from the instant of initial foot contact to the critical instant of take-off was measured for each subject and compared between groups. Outdoor subjects, despite a shorter step-close time, were shown to spend significantly more time in contact with the ground from plant to take-off. Outdoor subjects spent 0.38 seconds in the plant and take-off phase while indoor subjects only showed 0.33 seconds ($p<.03$). This further suggests that outdoor subjects do not receive as much force from the impulse created to decrease horizontal momentum. Because impulse is equal to the product of force and time and time is larger in the outdoor condition, then force must be decreased under that same condition.

Comparisons between indoor and outdoor groups showed no significant differences in hip or knee flexion displacements. The indoor and outdoor subjects flexed their right hip to an angle of 114.04 degrees and 109.59 degrees respectively and the right knee to 112.76 degrees and 113.06 degrees respectively. These results are similar to those shown by Martin & Stull (1969) who looked at the effects of knee angle on vertical jump performance. Jump heights were tested using 65, 90, and 115 degree angles at the knee joints. It was found that a knee angle of 115 degrees resulted in the best vertical jumping performance followed by a 90 degree knee angle and the worst results were caused by the 65 degree angle. This contradicts other studies that have suggested the ideal angle of knee flexion to be 90 degrees (Alexander & Seaborn, 1980; Heess, 1964). A greater amount of flexion at both the knee and hip provides for a greater range of motion for force production through which more force can be generated into take-off and places the hip and knee extensors on a greater prestretch generating a stronger stretch reflex. The study by Martin & Stull (1969) tested the vertical jump without using a countermovement. Subjects were instructed to hold the squat position momentarily before jumping in order to eliminate the effects of the stretch shortening cycle. Several studies have shown that a countermovement increases the height of a vertical jump (Morton, 1952; Khalid et al., 1989; Harman & Rosenstein, 1990). A study by Morton (1952) showed a countermovement to increase jump height performance by 5.84 cm by placing the extensors of the knee, hip, and ankle on a forceful pre-stretch. For this reason, it is understandable for Martin & Stull to have conflicting results from other studies. In order to elicit a large enough pre-stretch of the muscle to activate the stretch shortening cycle, larger ranges of motion must be achieved to place the muscle on that stretch (Chu, 1998). Therefore, when a countermovement is included in the jump protocol it makes sense that greater amounts of flexion at the knee closer to 90 degrees will further increase jump performance by increasing the stretch on the quadriceps muscle group, therefore increasing the contribution of the stretch shortening cycle.

It is important to note that optimal depth of the crouch is determined by quadriceps strength which may limit the depth shown in female volleyball players. A recent study looking at the biomechanics of the vertical jump showed a significant relationship between the muscular strength of the knee and hip extensors and the peak amount of flexion occurring at the knee and hip respectively during a standing vertical jump (Aragon-Vargus & Gross, 1997).

Only angles on the right side of the body were measured and used for comparison for the reason that the left side of the body was not always visible from one or both video cameras during the video capture process. Although the Peak 5 system is able to interpolate these missing points, accuracy is reduced and the left side is best avoided to maintain the validity of these results (Peak Performance Technologies, 1994). As well, displacements and velocities occurring at the ankle joints were not measured due to an inability to accurately identify the position of the lateral malleolus (true ankle joint) in the outdoor condition. As the foot plants and moves through the plant phase the sand is displaced and the foot sinks making the necessary landmarks for the true ankle joint too difficult to identify.

The angle of the trunk was also measured against the vertical plane as an indicator of trunk flexion during the plant phase. The outdoor subject group showed significantly more trunk flexion than the indoor group with 27.22 degrees of flexion versus 19.89

degrees of flexion. A greater amount of trunk flexion is usually advantageous to an athlete as it would allow her a greater range of motion or a greater duration of force production into extension usually yielding higher peak amounts of force or in this case a higher peak angular velocity of the trunk.

Take-off phase

In the volleyball spike, the take-off phase is the most dynamic movement of the skill. It consists of all movements which occur after the plant, beginning with trunk extension, then shoulder flexion and followed in order with hip and knee extension, then ankle plantar flexion. Throughout these movements, the arms continue to flex forward and upward at the shoulder joint and the center of mass is raised to its highest point within the body. The take-off phase concludes at the instant that the athlete becomes airborne and can no longer apply forces down on the ground. At this point, the athlete can no longer change the outcome of the jump. The take-off phase for an outdoor and indoor subject is shown in sequence in Figures 5.6a and 5.6b respectively.

In order to maximize the height of the jump, the volleyball player needs to increase the vertical velocity of her center of mass as much as possible prior to take-off. This is accomplished by rapid extension of the trunk, hip, knee, and ankle joints along with a fast upward swing of both arms (shoulder flexion).

The other component that makes up the initial velocity of the athlete at take-off is the horizontal velocity of the center of mass. This is a force that will act in the

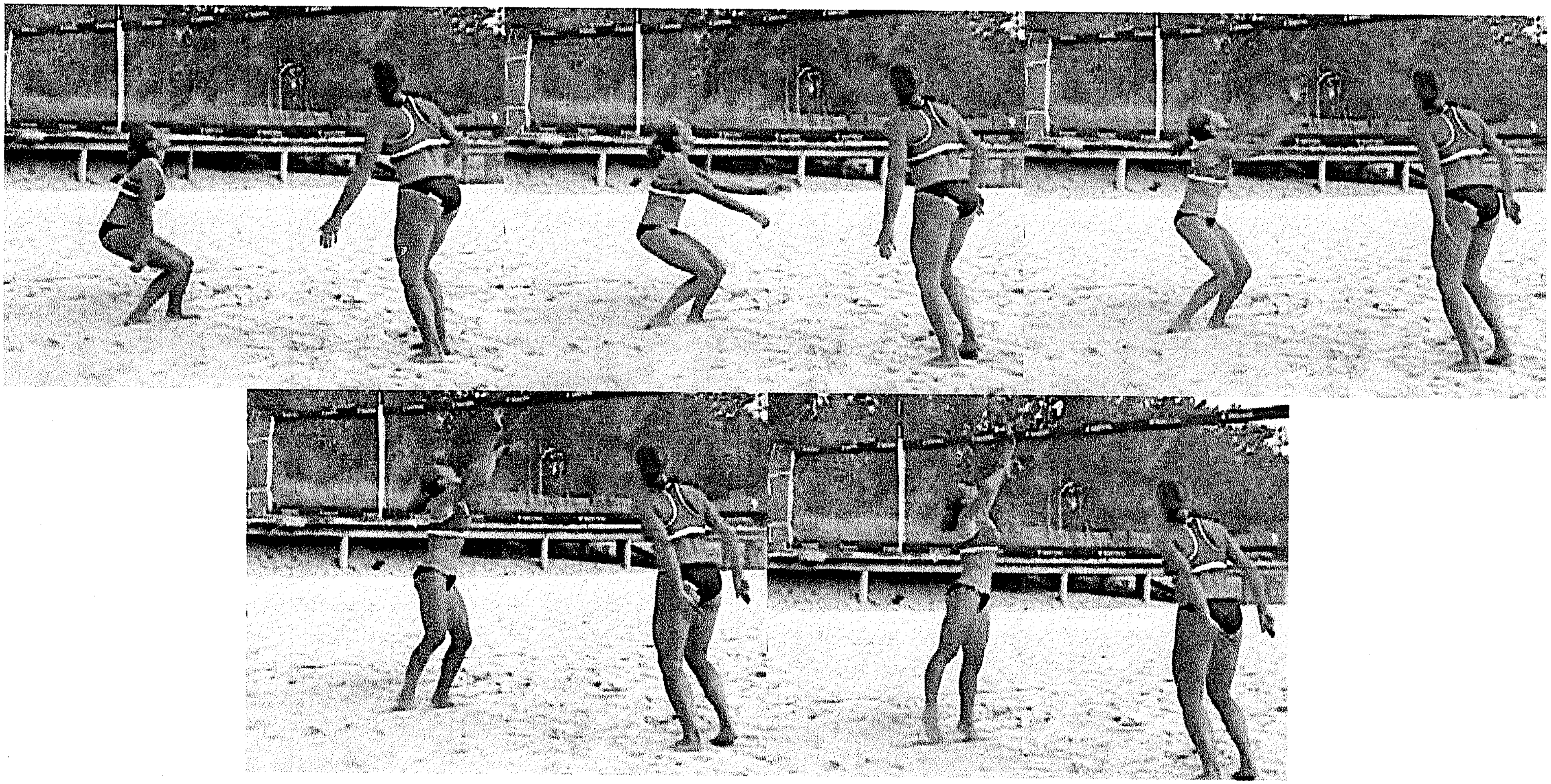


Figure 5.6a: Take-off phase (force producing phase) of an outdoor volleyball spike.

Figure 5.6b: Take-off phase (force producing phase) of an indoor volleyball spike.

x-direction and will cause the athlete to drift forward (horizontally) during the airborne phase. Both the vertical and horizontal velocity components summate together to equal the initial velocity of the volleyball player's center of mass which has both a certain magnitude and direction. In order for a volleyball player to maximize the height of her jump, she needs to increase her vertical velocity, while decreasing her horizontal velocity. This is similar to the concept of a high jumper who wishes to jump as high as possible to clear the high jump bar (Dapena, 1988).

An ideal take-off phase requires high peak angular velocities at the shoulders, trunk, hips, knees, and ankles in order to accelerate the body upward at a rate that will increase ground reaction forces as much as possible. The ground reaction force is the inverse of the product of the mass of the athlete in kilograms multiplied by the acceleration of the center of mass upward. Therefore, because the athlete is unable to alter her mass, she can only increase the rate of acceleration of her center of mass by increasing ground reaction forces.

It is important to note that the quality of the movements occurring up to this phase, including all of the backswing movements during the plant phase, will largely impact the efficiency of the force producing movements in the take-off phase.

During the take-off phase only two variables were found to be significantly different between indoor and outdoor subject groups, the height of the center of mass relative to the subject's body height and the horizontal velocity of the center of mass, both at take-off. Indoor subjects were shown to raise the height of their center of mass 2.74 percent higher than outdoor subjects. As Dapena (1988) discusses in regards to high jumping, an athlete's ability to raise his or her center of mass to higher heights within the body is indicative of a more talented high jumper. In the spike, how high an athlete can raise her center of mass is predetermined by body build and leg length, but can only be increased by the range of shoulder flexion that drives the arms upward over the head and by the extension of the trunk, the hip, and knee joints and plantar flexion of the ankles. Driving both arms high above the head and fully extending the trunk and legs will result in the highest possible position of the center of mass at take-off.

Although not significantly different, indoor subjects did show higher mean amounts of extension at both the trunk and hip, while the knee joint remained slightly more flexed (ankle was not measured) as well as a greater amount of shoulder flexion.

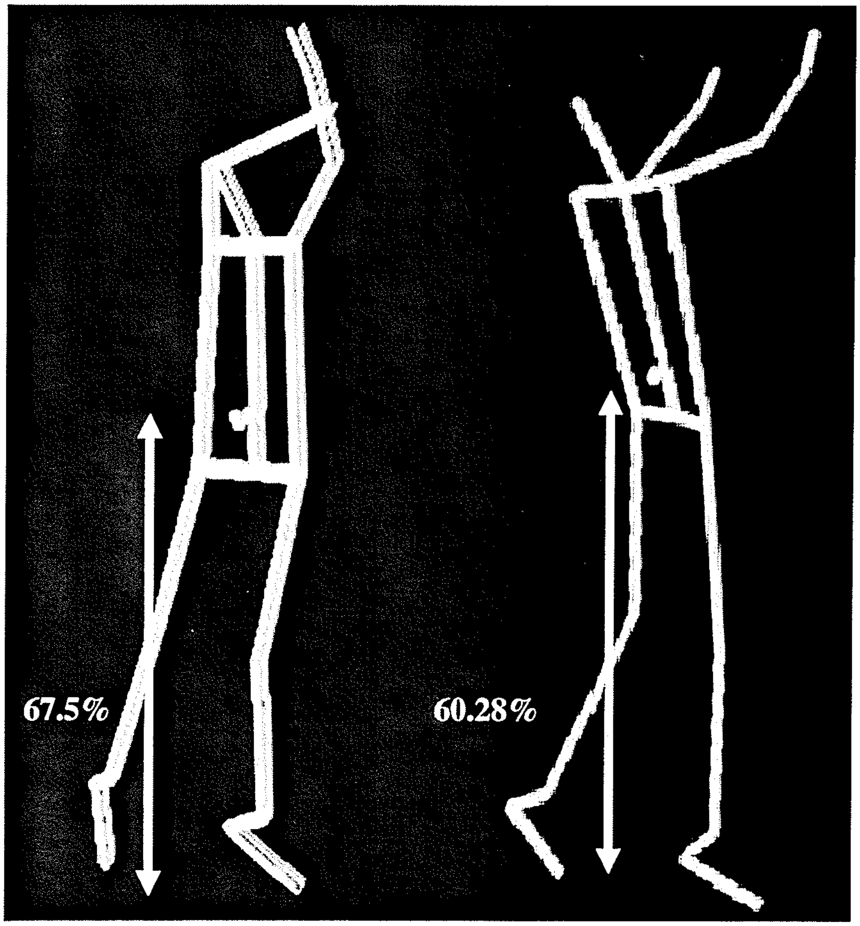


Figure 5.7: Stick figure A represents indoor player, B represents outdoor player, both at take-off. Center of mass is indicated by small dot on trunk. Note difference in the position of the center of mass between subjects due to different body positions (i.e. arm drive).

These factors combined are responsible for the significant difference in the height of the center of mass at take-off between indoor and outdoor subjects. Figure 5.7 compares the height of the center of mass for two take off positions; indoor (A) and outdoor (B). This illustration can be used to further understand the importance of a high arm drive and full extension of the legs in increasing the height of the center of mass. The indoor subject (A) in Figure 5.7 has raised her center of mass to a height of 67.5 percent of standing height while the outdoor subject (B) shows her center of mass at a height of 60.28 percent of standing height. The indoor player's ability to successfully raise her center of mass higher is caused by a higher position of both arms produced by a greater amount of flexion and abduction in both shoulders as well as a more vertical trunk position compared to the slightly hyper extended position of the outdoor subject. For comparison sake, high jumpers demonstrate some of the most effective techniques for raising the center of mass during the take-off phase. They are able to raise their center of mass to heights between 70 and 75 percent of standing height (Dapena, 1988). Heights of the center of mass of this extreme are not possible for volleyball players to achieve because of the two foot take-off. High jumpers utilize a one foot take-off driving the knee of the free leg up to further raise the center of gravity and increase ground reaction forces. With a two foot take-off volleyball players are not able to use the same knee drive and must rely more on driving both arms up and fully extending the body and trunk as vertical as possible.

Indoor subjects were also found to have a higher horizontal velocity of the center of mass at take-off with a mean velocity of 1.68 m/s versus 0.92 m/s ($p<.05$). The result of this will be a relatively lower take-off angle for indoor players and therefore, a greater amount of horizontal drift. It is important to recall the approach phase in which indoor subjects showed a significantly greater initial horizontal velocity as they entered into the plant phase. With an initial horizontal velocity of 3.32 m/s ($p<.05$), indoor subjects were able to decrease their horizontal velocity by 1.64 m/s. These horizontal velocities entering the plant are almost 28 percent larger than the values measured by Ridgway and Hamilton (1991) that looked at a mix of elite and recreational volleyball players. The subjects in the present study were all of elite caliber and it is not surprising that they showed higher horizontal velocities. On the other hand, outdoor subjects entered the plant phase with a horizontal velocity of 2.74 m/s ($p<.05$) therefore decreasing it by 1.81 m/s. As discussed earlier this statistic can be misleading as it incorrectly appears as though outdoor subjects demonstrate a more effective plant phase by decreasing horizontal velocity more than indoor subjects. Time must be taken into account when looking at the application of an impulse to change momentum or in this case, horizontal velocity. In the present study, outdoor subjects completed the plant and take-off phases 0.05 seconds ($p<.05$) slower than indoor subjects. This larger amount of time for a given impulse to occur will result in a smaller amount of force being applied over a longer period of time. This generates smaller peak absorption forces within the legs and a less effective pre-stretch of the knee and hip extensor muscles.

Airborne phase

The airborne phase is often referred to as the follow through movements of the jump and refers to all movements occurring from the time the athlete leaves the ground up until she lands from the spike. In this study, airborne movements involving the hitting action used to contact the ball were not analyzed. Only movements leading up to the airborne phase can affect the outcome of the jump and the airborne phase itself was only used as a measure of performance. It is during this phase that peak height of the jump is reached and the amount of horizontal drift could be measured. For the sake of explanation, the movements of the airborne phase are shown in Figure 5.8a for the outdoor spike and in Figure 5.8b for the indoor spike. The most important variable measured during this phase was the peak vertical displacement of the center of mass which has already been discussed as the determinant for jump performance and the dependent variable of this study. During this phase, the distance of horizontal drift was also measured as the linear displacement of the left toe from take-off to landing. Understandably, because indoor subjects showed a greater amount of horizontal velocity at take-off, they were also found to have a significantly greater amount of horizontal displacement (1.185 m versus 0.76 m; $p<.05$).

Up until now, horizontal velocity of the center of mass at take-off has been explained as strictly a hindrance to jump performance or a tell-tale sign that forces were not generated directly vertically at take-off, reducing jump height. It also increases the risk of contacting the net by drifting towards it, or increases timing difficulties between the path of the ball, the approach, and the angle of take-off as it now possesses horizontal velocity. A major advantage to some horizontal drift at take-off is that the horizontal velocity of the body is added to the linear velocity of the hand at contact with the ball. Although the upper body spiking movements are not the scope of this study, it is important to mention that horizontal drift will increase the velocity that the ball can be hit. For this reason, many indoor volleyball players are often encouraged to drift into the

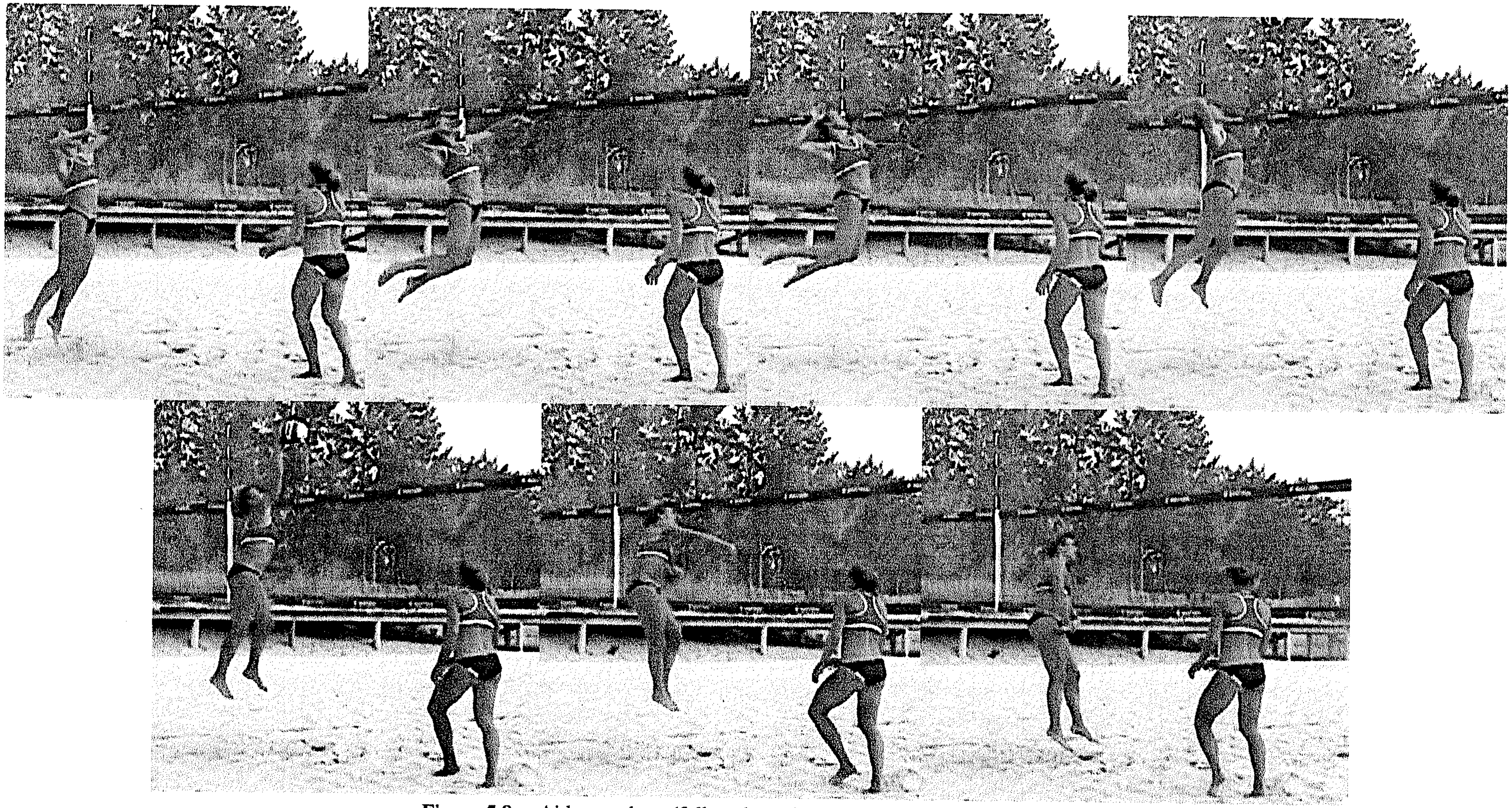


Figure 5.8a: Airborne phase (follow through) of an outdoor volleyball spike.

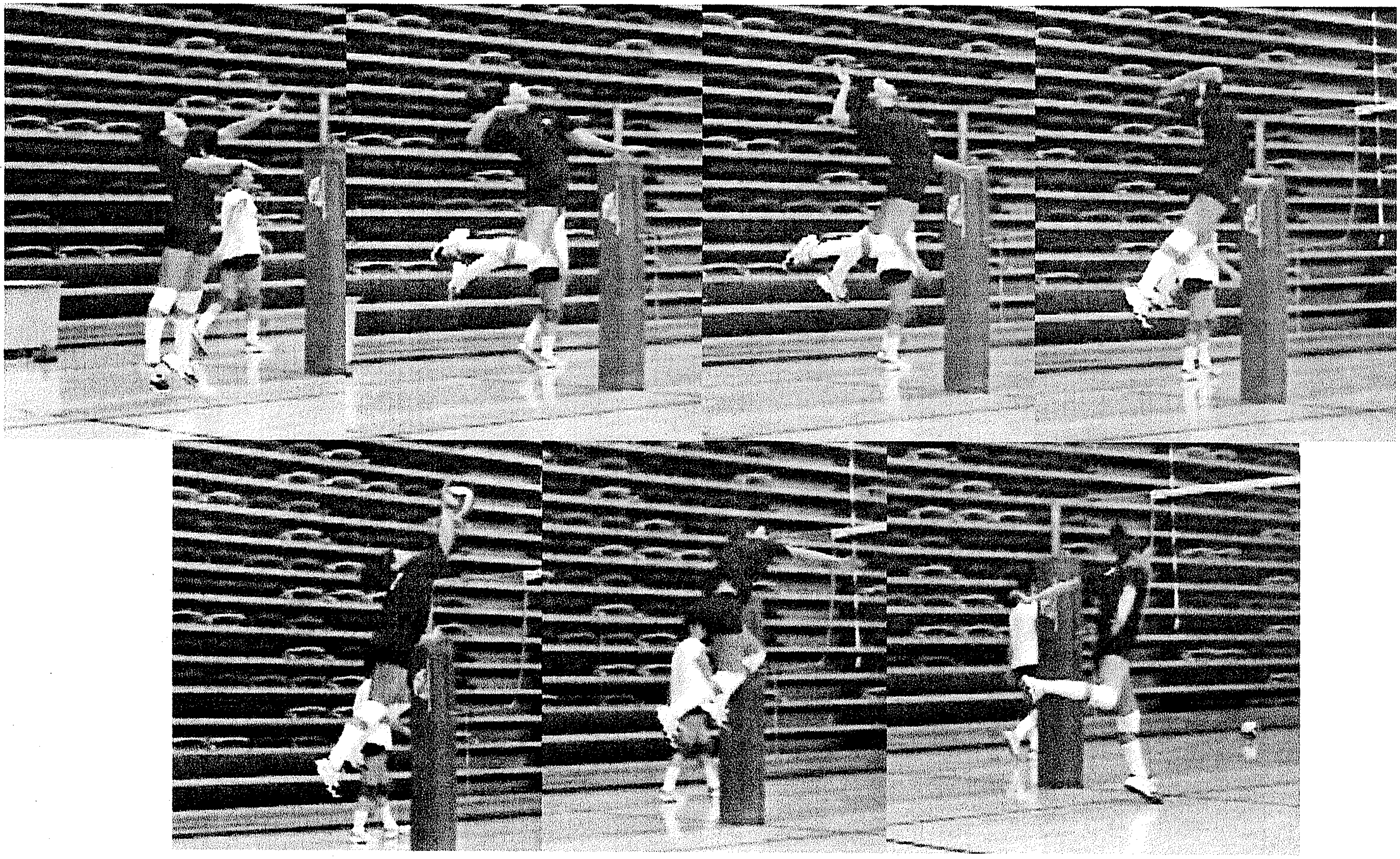


Figure 5.8b: Airborne phase (follow through) of an indoor volleyball spike.

ball with horizontal velocity. In relation to the jumping mechanics of the approach and take-off this will reduce jump height. However, it is recommended that the goal is not to completely eliminate horizontal velocity but to minimize it in order to maximize vertical velocity while still adding some horizontal velocity to the hand velocity at contact.

Correlation of Variables with Jump Height

Several variables were shown to be related to jump height in either the indoor or outdoor subject group conditions. This was tested and shown using a Listwise Correlation test followed by a forward stepwise regression analysis.

Step-close time vs. vertical displacement of the CM

In the indoor spike condition a strong negative correlation was seen between the length of the step-close time and the vertical displacement of the center of mass (-0.804). A slightly weaker, but negative correlation was also calculated between the two variables for the outdoor subject group (-0.510). This indicates that the faster the step-close occurs or the less time it takes for the trail leg to plant next to the lead leg, the higher the indoor athlete will jump. This finding is explained by the relationship to impulse and its unique effect on jumping skills. The less time spent on the ground and the faster the impulse (force x time) occurs, the higher the amount of force the athlete will be able to generate down on the ground and in turn, the higher the athlete can jump. One way to achieve this, as described by Dapena (1988) in a vast study looking at the biomechanics of the Fosbury flop, is to gradually lower the center of gravity during the approach. At the end of the approach, as the athlete plants her foot she will posses some small amount of downward or negative velocity along with forward velocity. Therefore, it makes sense that for a given amount of change in vertical velocity, the athlete who enters the plant with less negative vertical velocity to begin with will be able to generate higher amounts of upward vertical velocity at take off. By entering the plant with a lower position of the center of mass to begin with, a volleyball player will be able to begin force production sooner after plant and generate higher velocities into take off.

As described by Coutts (1978) all indoor subjects in the present study demonstrated a fast step-close. Although Coutts concluded in his study that there were no significant differences in jump height between step-close types, he did find that higher absorption forces were applied to the lower body during the use of the "hop" technique and the "fast-step close". This would further suggest that the extensor muscles of the knee and hip, along with the planar flexors of the ankle would be forced to contract eccentrically with greater force in order to sustain the high downward forces acting on the lower body over a shorter period of time. This more forceful eccentric contraction will, according to Chu (1998), elicit a more powerful stretch reflex in the same muscles causing them to contract concentrically and shorten at faster rates. A faster, more forceful contraction of the knee/hip extensors or the ankle plantar flexors will lead to higher angular velocities at the hip, knee and ankle along with higher vertical accelerations of the center of mass which result in greater ground reaction forces pushing up on the athlete.

Total time from plant to take-off vs. vertical displacement of the CM

The 2nd strongest correlation seen in the indoor group with vertical jump height was with the total time from when the initial foot plant occurs up to take-off. The strong negative relationship between the two variables suggests that the faster the athlete can move through the plant and take-off phases the better jump performance will be. Similar to the step-close, speeding up the transition between these two phases and the time to complete them will result in an impulse applied over a shorter period of time which consists of higher forces applied for less time. This is ideal for jumping and will result in higher jump heights (Dapena, 1988). It is also important to point out that range of motion can not be jeopardized in order to improve step close time or the time from plant to take-off. The same amounts of trunk, hip, knee, and ankle range of motion must be achieved beginning with large amounts of flexion during the crouch. This is still necessary to reach high angular velocities at these joints during the take-off and therefore higher peak vertical velocities and accelerations of the center of mass.

Peak angular velocity of the trunk vs. vertical displacement of the CM

One of the next strongest correlations with vertical jump height found in the indoor condition was with the peak angular velocity of the trunk during trunk extension at the beginning of the take-off phase. The indoor subject group showed a mean angular velocity of trunk extension of 156.86 degrees per second. This is comparable to the trunk angular velocities found in a study by Miller (1976) which measured a mean angular velocity at the trunk of 148.41 degrees per second. In the present study, a positive correlation of +0.745 was found in the indoor group between the peak angular velocity of the trunk and the vertical displacement of the center of mass. The extension of the trunk during the take-off phase is the first upward movement of the body as it extends from the crouch. The higher the acceleration of the trunk upward, the faster the center of mass of the body will also accelerate upward since the trunk makes up over 50 percent of the body's total mass. This upward acceleration of the body generates a force downward on the ground that is equal to the product of its upward acceleration and the mass of the body accelerating. This is further explained in a study by Miller (1976), which showed the upward acceleration of the trunk to be directly responsible for the first peak or increase in the ground reaction force produced during a countermovement squat jump. The study showed that the higher the initial acceleration of the trunk, the higher the resulting ground reaction forces.

In the current study, upward accelerations of the center of mass or segments of the body were not calculated, nor were ground reaction forces. However, with the range of motion at the hips and knees similar among subjects, the assumption can be made that those athletes generating higher peak angular velocities of the trunk through the same range of motion would also yield higher upward accelerations of the trunk. If this is in fact the case, then it is likely that increases in angular velocity of the trunk during extension would lead to higher vertical jump heights. Miller (1976) measured the vertical acceleration of the individual segments of the body including the trunk during extension. The trunk was shown to accelerate vertically at 12.91 m/sec^2 with a peak angular acceleration of 3463 deg/sec^2. These values were found to occur at the bottom of the crouch as the trunk first began to extend. It is in this position that peak ground reaction forces are generated (Miller, 1976). With this in mind it is important for volleyball players to have well developed core strength and to focus on increasing strength in the back extensor muscle group. Due to large mass of the trunk and a long resistance moment arm when flexed forward in the crouch position, high torques must be produced by the back extensors in order to accelerate the trunk upward via back extension. This requires a significant amount of strength in the lower back to produce the movement. In order for this study to actually calculate the amount of ground reaction force generated by each subject's vertical accelerations of the trunk and center of mass, the researcher would need to measure the ground reaction forces using a force platform.

A relationship between peak angular velocity of the trunk and the height of the vertical jump was not shown in the outdoor group. If, in the outdoor spike, trunk extension plays the same role as it does in the indoor spike, than the upward acceleration of the trunk would result in a downward force acting through the lower body. The key difference between the indoor and outdoor spike conditions is the response of the ground to these downward forces. In the indoor spike, these downward forces act through the lower body onto the ground and the ground pushes back with an equal and opposite reaction force increasing jump height. In the outdoor condition, the downward force on the lower body drives the feet deeper into the sand. Instead of the sand applying an equal force back on the body, some of the force is used to displace the sand, pushing it downward, and the ground reaction force applied back on the feet is much less. This will produce lower vertical and horizontal ground reaction forces at take-off in the outdoor spike jump.

Shoulder angular velocity vs. trunk angular velocity

Under both conditions, indoor and outdoor subject groups both showed a strong positive relationship between the peak angular velocities of the shoulders as they flex forward from plant to take-off and the peak angular velocity of the trunk (+0.668 and +0.737 respectively). The armswing begins force production prior to the plant phase by beginning to swing forward during the last step. Once the initial foot plants, the arms accelerate downward then past the body and back upward. After the arms pass by the hips, the trunk begins to extend while shoulder flexion continues. In the current study, peak shoulder angular velocities were measured as 612.63 deg/s and 505.13 deg/s for the indoor and outdoor subject groups respectively while the same groups showed trunk extension angular velocities of 156.86 deg/s and 139.75 deg/s respectively. This study shows that for both indoor and outdoor volleyball, a faster arm swing is related to faster angular velocities of trunk extension and an increase in vertical jump height.

During vertical jumping, Miller (1976) found that the net ground reaction force exerted on the body exhibited a "double peaked" trend separated by a small decrease in ground reaction force between them. She suggested in her study that the use of an arm swing reduced the magnitude of each of the maximum peaks, however increased the magnitude of the force between them, creating a dip in the curve, and had an overall effect of increasing jump height. When the lower body is in an ideal position to exert vertical ground reaction force (deep crouch position), the upward acceleration of the arms due to the armswing creates a downward force on the body at the shoulders that acts to slow down the rate of shortening of the quadriceps and gluteal muscles (Feltner et al., 1999). According to the force-velocity relationship, slower concentric contractions of the leg muscles will result in a greater amount of muscular force production and therefore larger ground reaction forces. In the present study, a strong relationship between peak shoulder angular velocity and jump height was not found for either the indoor or outdoor subject groups, however there was a strong positive correlation in the indoor subject group of 0.75 ($p<0.01$) between the angular velocity of the trunk during extension and vertical jump height. In addition to this, positive correlations of 0.67 for indoor subjects and 0.74 for outdoor subjects were shown between the peak angular velocities of the shoulders and trunk. These results show that there is an important relationship between trunk angular velocity and jump height that may have increased by the use of the arm swing.

Horizontal velocity of CM; length of last step: position of foot plant in relation to CM vs. vertical displacement of the CM

With the indoor subject group, several variables measured during the plant phase of the spike approach were found to be of importance to the outcome of the jump. These included: the horizontal velocity of the center of mass prior to the initial foot plant, with a positive correlation of +0.526; the length of the last step with a positive correlation of +0.520; and the position of foot plant relative to the position of the center of gravity in relation to the when the right foot plants after the last step with a positive relationship of +0.650. According to Dapena (1988), as a high jumper approaches to plant for take-off, one of their main concerns is to increase the horizontal velocity enough so that when the take-off leg plants it continues to flex at the knee and hip as the ground reaction forces push back on the leg. Despite the athlete's efforts to extend at the knee for take-off, the knee continues to flex. This elicits a forceful eccentric contraction of the quadriceps and activates the stretch reflex within the muscle. The higher the horizontal velocity of the athlete at plant, the more forceful the eccentric contraction of the quadriceps will need to be in order to prevent the body from collapsing toward the ground and the more effective the stretch shortening cycle. This same concept can apply to the plant phase of the volleyball spike, with the only major difference being the two foot plant versus a single foot plant in high jump.

Higher horizontal velocities of the center of mass within volleyball players prior to the plant were associated with higher jump height results. This can be caused by a more forceful eccentric contraction of the quadriceps, hip extensors and calf muscles during the plant and a more powerful stretch reflex leading to a more forceful concentric contraction during extension of the hip, knee, and ankle.

In order to ensure that a volleyball player generates as much force vertically as possible to increase jump height, horizontal velocity needs to be used effectively and then decreased during the plant phase. As the horizontal velocity of the center of mass increases between subjects, the length of the last step must also increase. A longer last step allows the initial foot plant to occur farther in front of the line of gravity to produce horizontal braking forces in the opposite direction, back on the athlete. These braking forces are responsible for increasing the magnitude of the eccentric contraction of the quadriceps and for slowing the horizontal velocity of the athlete. The length of the last step for indoor subjects was also found to have a positive relationship with vertical jump height. The longer the last step, the higher the athlete can jump.

To further examine this concept, the relationship between the horizontal velocity of the center of mass at take-off (indicating how well the athlete decreased horizontal velocity) and the distance that the foot plants ahead of the line of gravity was measured. Although insignificant ($p<.09$), a negative correlation of -0.511 was found between the variables for the indoor group suggesting that as the foot is planted further in front of the line of gravity, the horizontal velocity at take-off is decreased. No relationship was found for the outdoor group.

As well, in order to increase the distance from the line of gravity to the foot at plant, the athlete will need to use a longer last step. The results from this study of the indoor group showed a significant positive relationship between step length and the position of the heel at foot plant relative to the line of gravity (+0.796; p<.004), while no relationship was seen in the outdoor group. The longer the last step, the further in front of the center of gravity the subject planted her foot.

What can be concluded in regards to the plant phase for the indoor group is that a faster approach with a higher horizontal velocity, combined with a longer last step allowing the foot to plant further in front of the line of gravity will result in larger horizontal ground reaction forces that act back on the body. These forces will attempt to slow down the athlete while the athlete's forward momentum will force the knees into a greater amount of flexion increasing tension in the quadriceps. This elicits a more forceful stretch reflex and decreases horizontal velocity, allowing the athlete to apply larger forces upward and jump higher.

In contrast, the outdoor subject group showed no significant correlations between horizontal velocity of the center of mass, the length of the last step or the position of foot plant relative to the center of mass with vertical jump height. The plant phase of the outdoor spike appears to require several changes from the traditional mechanics used in the indoor spike. When planting the feet outdoor, the softer sand surface and how it responds to the plant must be taken into account. Outdoor volleyball players have the same main goal as indoor players of increasing vertical velocity as much as possible at take-off in order to increase jump height, however, they must go about it differently. Indoor players are able to use horizontal velocity to their advantage with very little limit as to how fast they can enter the plant assuming they are physically strong enough to sustain the high eccentric loading of the quadriceps and gluteal muscles. Outdoor players on the other hand need to limit the amount of horizontal velocity that they bring into the plant. Excessive horizontal velocity cannot be decreased fast enough by the sand surface in order to quickly use the stretch shortening cycle and a large impulse consisting of high amounts of force exerted over a short period of time.

The faster the athlete approaches, the longer the last step needs to be and the further in front of the line of gravity the foot will plant. The more horizontal velocity the player possesses into the plant, the further in front of the line of gravity the foot needs to be planted in order to increase the horizontal component of the ground reaction forces to generate enough braking force to slow the athlete down. If this were attempted by the outdoor player, the initial response of the sand at foot plant would be to take on some of the linear momentum of the foot by displacing in the direction the player is traveling. This causes the athlete to continue forward and delays the flexion of the knee and hip joints so that the backswing phase of the plant takes a longer period of time decreasing the effects of the stretch shortening cycle and therefore decreasing the rate of transition from flexion to extension at the hip, knee and ankle. This is likely the reason that outdoor subjects in the present study showed faster step close times in an attempt to decrease horizontal momentum however significantly longer durations from plant to take-off ($p<.02$).

Differences seen between in the indoor and outdoor subject groups were mostly found in the plant phase. The plant phase is most affected in the outdoor spike due to the response of the sand to forces applied on it. As already mentioned any force applied on the sand surface will not yield an equal and opposite force back on the foot of the athlete because some portion of the force applied to the sand will be used to displace the sand. The larger the horizontal component of the force the foot applies to the sand is, the more sand will be displaced forward and the more difficult it becomes for the athlete to apply forces down on the ground in order to quickly begin to drive the body upward.

A 1988 study by Dapena looking at some of the U.S.A.'s top high jumpers explains that those jumpers who demonstrated large negative vertical velocities (downward velocities) of the center of mass at plant were not able to apply enough force to transition from downward velocity to upward velocity quickly. These high jumpers showed significantly lower jump heights ($p<.05$). This issue of timing is also discussed by Aragon-Vargas and Gross (1997) who conducted a study on fifty-one individuals performing a countermovement vertical jump and found that the amount of negative work done at the bottom of the crouch was not included in their final list of key variables affecting jump height. They attributed this lack of relationship to the timing of the peak negative impulse of the body center of mass relative to the deepest crouch position. If the delay between these two events is too long, the effects of the stretch-shortening cycle are less.

In the outdoor volleyball spike plant, displacement of the sand caused by the foot sinking deeper during downward/forward forces applied to the ground will cause the velocity of the center of mass to remain negative for a longer period of time. For this reason, faster horizontal velocities are not seen in the outdoor spike and there is no need for a longer step or for the foot to plant too far in front of the line of gravity. The more horizontal velocity, and therefore the greater the horizontal momentum that the volleyball player enters into the plant with, the more sand will be displaced and the larger the displacement will be. Some amount of the athlete's horizontal momentum is transferred to the sand at plant creating a disadvantage for the outdoor volleyball player who now will need to apply a force over a longer period of time in order to slow his horizontal velocity and momentum. Any increase in the length of time that the impulse is applied results in an equal decrease in the amount of force that is applied to the athlete during the impulse. Therefore, the sand cannot apply as much force back on the athlete as was applied to the sand initially at plant. This leads to a less effective plant and prestretch of the hip, knee, and ankle extensors. The more horizontal velocity a player possesses entering the plant, the further in front of the line of gravity the foot must plant to slow the athlete. As the angle at which the foot approaches the ground decreases, the horizontal component of the ground reaction force increases. The larger the horizontal component of the ground reaction force is, the more force is applied to the athlete to slow down. If outdoor volleyball players were to use this technique of a faster approach and a foot plant further in front of the line of gravity, a more horizontal component of force would be applied by the foot on the sand only causing an even greater displacement of the sand as opposed to a greater return of horizontal ground reaction forces.

Stepwise Regression Analysis

For this study, stepwise regression was used for statistical analysis of the effect of all independent variables on the vertical displacement of the center of mass. This means of analysis was chosen as the best measure for determining the key factors of related to jump performance because it takes into account not only each variable's relationship with the dependent variable, but also relationships that may exist between similar variables. Although other methods could also be used such as a principle components analysis, the stepwise regression method presents its findings in a much clearer manner that can be more easily understood and interpreted by the coach or reader. Stepwise regression is a common analysis tool that has been used in other studies examining the volleyball spike in order to find a set of variables that best predict jump performance (Dowling & Vamos, 1993; Aragon-Vargas & Gross, 1997).

Some limitations to the stepwise regression analysis do exist and should be understood. The addition or subtraction of individual variables from the variable set can cause large changes to the magnitude of the effect of other variables. Although those variables eliminated do not show a significant impact on the total variation they are not entirely obsolete and all together could be important. Finally, the variables chosen by the regression analysis should not be considered as the only contributors to jump height. Some removed variables could be functionally important and may only have been removed due to some correlation to other variables within the regression equation.

For the indoor group eight variables were selected by the forward step wise regression and only the five most significant have been included in the regression equation for predicting jump height. The regression equation is as follows:

$$\mathbf{y = 1.5 - 3.1 * x_1 + 0.016 * x_2 - 0.005 * x_3 - 0.001 * x_4 - 0.09 * x_5}$$

Where: y = vertical displacement of the center of mass (jump height)
x_1 = step close time (sec)
x_2 = peak ankle dorsi flexion (degrees)
x_3 = peak hip flexion (degrees)
x_4 = peak shoulder hyper extension (degrees)
x_5 = length of last step (m)

Indoor spike stepwise regression analysis

Stepwise regression analysis of the data set collected from the indoor subject group identified eight key variables out of the 25 measured that can be used to best predict the vertical displacement of the center of mass. The variable with the highest coefficient on jump performance was the step close time in the plant phase. A strong negative correlation coefficient suggests that volleyball players with a highly skilled spike jump will demonstrate a shorter duration of the step close. The faster the two feet plant together, the higher the vertical displacement of the center of mass will be.

Jacoby (1984) of Boise State University explains in terms of high jump that when jumping an athlete can generate a greater amount of power by exerting less force over a shorter period of time. In order for a volleyball player to achieve this, the same fast take off movements need to occur as in high jumping: The athlete needs to have high angular velocities at the shoulder joints as the shoulders flex and the arms are driven all the way over the head; the trunk needs to show high accelerations and reach high peak angular velocities during extension; and the legs must be strong enough to extend quickly.

Peak dorsiflexion angles in the ankles and peak flexion angles at the hip were the second and fourth most significant contributors to the total variance respectively. Both of these variables occur in the plant phase and are largely increased by a high horizontal velocity of the center of mass entering into the plant. With indoor volleyball players entering the plant phase with a mean horizontal velocity of 3.32 m/s they need to effectively decrease this horizontal velocity by increasing vertical velocity at take off. Again referring to the skill of the high jump take off, Dapena (1988) has suggested that horizontal velocity should be increased during the approach phase and should not begin to decrease until after the foot plant has occurred. At this time, horizontal velocity is only decreased as a result of the production of vertical velocity through the take off process. The way that a high jumper decreases horizontal velocity is similar to that of a volleyball player during the spike approach. The high jumper plants the take off foot with an initial heel contact. When the heel contacts, the foot should be in a neutral or slightly dorsi flexed position (Krahl & Knebel, 1979). After the heel contacts, the foot will passively pronate and progressive plantar flexion begins in the upper ankle joint. This heel to toe contact with the ground increases the time over which forces can be absorbed and can act to slow the horizontal velocity of the body down while forcefully increasing flexion of the joints within the legs.

A greater amount of flexion at the hip and knee results from a more effective plant phase and a greater amount of time for the horizontal momentum of the body to act against the horizontal ground reaction forces pushing back on the planted foot. The hip and knee are forced into a smaller angle due to the high impulses applied on the body to decrease its forward momentum. It is therefore reasonable that the stepwise regression analysis of this study showed increases in hip flexion angle to be one of the top contributors to jump height.

Increases in hip flexion, likely caused by a forceful pre-stretch of the hip extensor muscles, also leads to a more forceful concentric contraction of the same muscle group and higher angular velocities at the hip joint during extension into take-off. For this reason this study also identified angular velocity of the hip joint during extension to be included in the stepwise regression equation. Other important variables that may have been overlooked by the stepwise analysis due to colinearity, or their close relationship to peak hip angular velocity, include the angular velocities occurring at the knee and ankle joints. Statistical analysis of the data collected from the ten indoor subjects showed strong positive correlations of .889 and .979 between hip and knee angular velocities and knee and ankle angular velocities respectively. Proper jumping mechanics demonstrate segmental movement and the summation of forces from the most proximal to most distal joints. Therefore, peak hip angular velocities should precede but lead to higher knee angular velocities and therefore higher ankle angular velocities. Other studies have been shown to support these findings that the hip extensor muscle group is most closely related muscle group to vertical jump performance (Aragon-Vargas & Gross, 1997; Pandy & Zajac, 1991).

A study by Aragon-Vargas and Gross (1997) showed increases in hip flexion to be significantly correlated with higher amounts of peak torque at the hip joint ($p<.05$). They also found that the amount of flexion the subject could achieve during the crouch was also dependent on how much power the hip extensor muscles could potentially produce.

Shoulder hyper-extension was also selected by the stepwise regression analysis as the third most important variable in the regression equation. The importance of the amount of shoulder hyper-extension occurring during the approach is related to two other variables measured in this study. The further the arms are extended behind the body to begin force production, the greater the range of motion there will be for shoulder flexion to occur. A larger range of motion allows the arms to accelerate for a longer range increasing peak angular velocities at the shoulder. This will help to increase the vertical acceleration of the center of mass and to increase the downward force on the lower body that increases the eccentric contraction in the quadriceps by forcing the legs into greater knee flexion. Increases in shoulder hyper-extension are also commonly related to higher amounts of trunk flexion during the plant. When the arms are extended back behind the body they posses some angular momentum that must be decreased quickly at the end of the range of motion. When the arms reach this point, some of their angular momentum may be transferred to the trunk, forcing it into more trunk flexion. Increases in trunk flexion will increase the pre-stretch on the back extensors while also increasing the range of motion for trunk extension, causing higher trunk accelerations upward.

The length of the last step has already been discussed in depth and is again included as one of the eight variables identified by the stepwise multiple regressions. The plant phase is critical to the outcome of the jump as it consists of all backswing movements that will directly impact the quality of force production. A longer last step and greater distance of foot plant in front of the line of gravity are both related to one another and correspond to a faster horizontal velocity entering into the plant. Similar to high jump, when the foot plants the forward momentum of the volleyball player forces the legs to flex stretching the extensor muscles of the knees (Dapena, 1988). This stretch on the muscles stimulates the muscles and will later help to increase the force of extension during the take-off phase. If the last step is not long enough to plant the foot out in front of the body the athlete either has not generated enough horizontal velocity during the approach or there will not be an effective braking phase of loading of the legs during the plant.

The final variable to be discussed for the indoor subject group is the height of the center of mass at take-off (relative to standing height). Indoor subjects were shown to raise their center of gravity to an average position of 62.3% of standing body height. In Dapena's analysis of high jump (1988), he suggests that the height the center of gravity will reach on the jump is determined by the height of the center of gravity at the end of the take-off and the vertical velocity of the center of mass. In the same study, Dapena shows high jumpers raise their center of gravity as high as 70-75% of standing height. This is considerably higher than the results of this study due to the differences between the one foot take-off in high jump versus the two foot take-off of the volleyball spike. The one foot take-off in high jump allows the free, unweighted leg to be driven vertically contributing to the height of the center of mass. A volleyball player needs to rely solely on full extension of the limbs and the upward drive of both arms high above the head to maximize the height of the center of mass at take-off.

Only five variables were included in the equation as they statistically accounted for 99.6 percent of the total variance in the vertical displacement of the center of mass. The addition of more variables would provide only a small increase in the accuracy of predicting the dependent variable.

Outdoor spike stepwise regression analysis

In the outdoor spike group only 23 independent variables were added to the model with the outcome variable also being the vertical displacement of the center of mass. Ankle angles and velocities could not be measured due to the difficulty of accurately completing the digitization process of the ankle segment when hidden beneath the sand.

The results of the regression analysis for the outdoor group were not as compelling as those shown by the indoor data set. Only two variables were selected as the key contributors to jump height in the outdoor condition: the vertical velocity of the center of mass at take-off; and the step close time.

Vertical velocity of the center of mass does not need any further explanation as it is directly related to vertical jump height and is unarguably the best predictor. It is important to note that this same variable was removed from the indoor data set during the stepwise process. This was likely due to its close relationship to several other variables that relate to vertical velocity in the same way that they relate to the displacement of the center of mass. The fact that it was not removed from the outdoor group is the result of a larger variance between subjects in the outdoor condition. This larger variance illustrates the varying technique used by outdoor players and further explains the difficulty of drawing correlations between any two variables and the need for further research and the development of technique in the sport of beach volleyball.

Step-close time was found to be the second strongest predictor of jump height for the outdoor spike condition. Identical to the indoor game, the faster the step close can occur, the faster force production can occur and the greater the amount of power that can be generated for the jump. In addition to this, and specific to the outdoor condition, another cause or need for a faster step close is to increase braking forces and slow horizontal velocity using the plant of both feet. In the indoor condition the initial foot placement is able to plant further ahead of the line of gravity and take on greater amount of braking force. When the foot plants initially in the sand, the sand is displaced forward and the momentum of the athlete is not decreased as quickly. Therefore, the impulse of the athlete should be to plant the second foot as quickly as possible to help decrease horizontal momentum. While this may be an alternate cause for faster step close times, it can be an advantageous adaptation to the volleyball spike technique as it allows the outdoor athlete to decrease a greater amount of horizontal momentum, maintain balance in the sand, and increase the rate of contraction of the leg muscles.

CHAPTER 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The purpose of this study was to determine the kinematic differences between the outdoor (beach) volleyball and the indoor volleyball spike approach and takeoff. This was accomplished by identifying those variables that are most responsible for improving jump performance, measured as jump height in the indoor condition, and then comparing all variables measured in the indoor subject group to those measured in the outdoor subject group. A subpurpose was to use this information to provide coaching assistance: to minimize the decrease in performance that is seen in outdoor volleyball spiking. The two hypotheses formulated for this study were that: (1) the biomechanics of the beach volleyball spike approach would not differ from the indoor spike approach; and (2) Peak vertical jump heights would not be significantly different between indoor and outdoor subject groups.

Ten elite female indoor volleyball players: seven recruited from the Canadian Women's National Volleyball team; and three from the University of Manitoba Women's Volleyball Team, were used to make up the indoor subject group. The outdoor subject group consisted of ten female beach volleyball players who were selected at the 2004 Senior Open National Championships in Beach Volleyball held in Wasaga Beach, Ontario, Canada. All 20 subjects provided an accurate representation of the top female volleyball players across Canada in their respective sport: indoor or beach volleyball. The data collected from these subject groups represents as close as possible the ideal technique used in the spike approach and take off for indoor and outdoor volleyball.

Twenty three descriptive variables were measured in each group using two camera video analysis techniques including the calculation of three-dimensional coordinates with the Peak 5 software from Peak Technologies (Peak Technologies, 1994). When comparing the means of these variables between experimental groups, several significant differences were identified.

The outcome variable of jump height, used as the dependent variable for each group and the key measure for jump performance, was shown to be significantly different between groups. Outdoor players showed a decrease in jump height of 12.7 percent when compared to the indoor subject group. This finding leads to rejecting the second hypothesis that there would be no difference in jump height between groups.

During the approach phase of the spike two variables were shown to have a significant difference between the two groups. They included the horizontal velocity of the center of mass prior to the initial foot plant and the length of the last step.

Most of the differences seen in the outdoor spike as compared to the indoor spike were measured during the plant phase of the skill. In the plant phase, three variables produced a significant difference between groups. The step-close time, or the time lapse between the first and second foot contacts for the outdoor subject group was found to be only two thirds the length of time of the indoor step-close (33.3% faster). Interestingly however, the total time from when the first foot plants to when the take-off phase is completed by the athlete leaving the ground was found to be significantly longer in the outdoor group despite a faster step-close. This suggests that the excess time delay in the outdoor spike would be due to a slower take-off phase (force production) or from a slower transition from backswing to force producing movements and not from the plant itself. A slower transition from the eccentric contraction of the hip, knee and ankle extensors to the concentric contraction or extension of these joints decreases their ability to utilize the benefits of the stretch shortening cycle to its full potential. The faster the rate of this eccentric contraction, the more forcefully extension can occur (Chu, 1998).

The final significant difference found between groups in the plant phase was the peak amount of flexion in the trunk during the crouch. Outdoor subjects were found to have a greater amount of trunk flexion with a mean difference between groups of 7.3 degrees measured from the vertical. This increases the range of motion of trunk extension that is available to outdoor volleyball players during the force producing take-off phase. Accelerations of the trunk upward are critical to increase the force that the legs can apply downward on the ground. In order to reach high accelerations of trunk extension, high levels of muscular strength of the back extensors is required. It is possible that many female volleyball players do not posess the necessary strength to extend the trunk from a more flexed position. As the trunk increases in flexion, the moment arm of the resistance force (weight of the trunk) increases and more back extensor torque is required to lift the trunk vertically. This requires greater core strength in elite female volleyball players.

During the take off phase, no significant differences were found between groups for the kinematics of the trunk, hip, or knee joints. The only significant differences determined for the instant of take off were the horizontal velocity of the center of mass and the height of the center of mass relative to body height. Indoor subjects were able to raise their center of mass seven percent higher from standing height than outdoor subjects to a mean position of 62.3 percent of standing height. The horizontal velocity of the center of mass was significantly greater prior to the plant phase and remained significantly greater through take off. Indoor subjects left the ground with a mean horizontal velocity of 1.68 m/s versus only 0.92 m/s for outdoor subjects. This is 45.2 percent less horizontal velocity in the beach volleyball spike take-off.

During the airborne phase, very few variables were measured as the hitting action of the upper body and the accompanying movements of the lower body were not examined in this study. The only two variables of interest in this final phase included the displacement of the center of mass vertically (dependent variable) and center of mass displacement horizontally (horizontal drift). The vertical displacement of the center of mass has already been discussed while the horizontal drift was significantly larger in the indoor subjects who also demonstrated a higher amount of horizontal velocity at take off. A large amount of horizontal velocity at take off is not ideal in correct spike technique as it indicates that maximum force was not generated directly vertically to maximize jump height but at an angle to the vertical.

Key variables related to jump height

Correlations between all variables and the vertical displacement of the center of mass were calculated independently for indoor and outdoor groups to determine which variables showed a significant relationship with jump height.

The results for the indoor group showed only five variables to be significantly correlated with jump height, ignoring the relationship between the vertical velocity of the center of mass at take off and the vertical displacement of the center of mass after take off because of their direct relationship with one another. The strongest correlated variables with jump height were: (1) step close time; (2) the total time from plant to take off; (3) the peak angular velocity of the trunk during the take off phase; and (4) the position of the initial foot plant relative to the center of mass. It is important to note that three of these variables; step close time, the total time from plant to take-off, and the position of foot plant relative to the center of gravity all lie in the plant phase, with the latter two also showing a significant difference between indoor and outdoor groups. Movements occurring during the plant phase appear to be some of the most important variables of the volleyball spike in increasing jump height. This is the phase of the skill when all backswing movements occur in preparation for force production. The more efficiently the backswing movements are performed the more effective force production will be and therefore the greater the resulting jump. Differences between the indoor and outdoor spike that lie in the plant phase are likely to have a significant impact on performance as they will determine the potential for a skilled spike as the following phases occur.

Correlations were also calculated between the variables measured from the outdoor group and their jump height performance. The results of this portion of the study indicated that the only variable found to be significantly correlated with jump height was the directly related vertical velocity of the center of mass at take off. The only other variable to show a fairly strong positive but not significant relationship was the most highly correlated variable in the indoor group. This was the step close time which showed a negative correlation of -.518. This suggests that as step close time decreases, vertical jump performance increases. A lack of significant relationship between the variables measured and the outcome of the spike for the outdoor group may confirm the finding that the volleyball spike approach and take off is not performed the same by outdoor players in the sand as it is by indoor players on the hardwood court.

Stepwise regression analysis

In order to determine the variables most related to changes in jump height, a forward stepwise regression analysis was conducted on all indoor and outdoor variables independently.

Using the technique of the indoor volleyball spike approach and take-off as the ideal way to perform the skill, eight variables were identified to be the most important when trying to increase vertical jump performance. These eight variables identified by the stepwise regression analysis as the group of variables that together explain nearly all of the variance within the vertical displacement of the center of mass. They are listed from most important to less important:

1. step close time
2. peak amount of ankle dorsi flexion in plant
3. peak hip flexion
4. shoulder hyperextension
5. length of the last step
6. height of the CM at take off
7. peak hip angular velocity
8. the position of the foot plant relative to the CM

The same statistical analysis of the outdoor subject data set identified only step close time as the most critical variable for increasing jump height.

Conclusions

Based on the results of this study, the following conclusions appear to be justified:

1. Outdoor volleyball players show lower jump heights than indoor players when performing a spike approach and take off.
2. Outdoor volleyball players demonstrate a slower approach with less horizontal velocity as they plant their feet.
3. The last step into the plant is significantly shorter for outdoor players than indoor players.
4. Step close time was shorter, indicating a faster step close for outdoor players planting in the sand than indoor players on the hardwood floor.
5. Outdoor volleyball players, despite a faster step close, do not move through the plant and force production as quickly as indoor players. Force production occurs more slowly.
6. All hip and knee displacements and angular velocities did not significantly differ between subject groups, so the basic techniques during leg extension are similar.
7. Trunk flexion during the plant was greater for outdoor players than indoor who remained more vertical.
8. Outdoor players were not shown to raise their center of mass as high within their body prior to take off.
9. Outdoor volleyball players demonstrated less horizontal drift during the jump. The airborne phase was more vertical for the outdoor subject group. This is directly related to the amount of horizontal velocity at take off.

10. Step Close time was found to be the most important variable for predicting jump height in both the indoor and outdoor volleyball subject groups
11. Angles of dorsi flexion at the ankles and flexion of the trunk were key predictors of jump height in the indoor condition but did not show any relationship with jump height in the outdoor condition.
12. The length of the last step and the height of the center of mass at take-off were the final critical components for predicting jump height for indoor, female volleyball players. However no relationship was shown for these variables in the outdoor condition.
13. When interviewed, outdoor volleyball players appear to be aware of several key differences between the volleyball approach and take-off of the indoor and outdoor game. The most common points noted by beach volleyball players is that the approach is slower and that the vertical jump is closer to straight up and down than in indoor where players show a lot more drift.

Recommendations

The following recommendations are suggested for future studies on the beach volleyball spike approach and take off:

1. When indoor players are used for skill analysis, tight fitting attire of contrasting colors should be worn during filming in order to increase the clarity of joint positions when digitizing the video for analysis. This is not a problem for outdoor players who are required to wear tight fitting clothes as uniform.

2. Studies need to be done analyzing the biomechanics of the hitting action including all body movements during the airborne phase for the outdoor spike and comparison of these to the indoor spike technique.
3. Strength tests could be performed for the trunk, shoulder, hip, and knee to help identify differences in technique and performance that are caused by varying amounts of strength and the ability to produce force between subjects or groups.
4. A closer analysis of the sand's reaction to forces that are applied to it by the foot from plant to take off would increase knowledge of how the sand surface affects the biomechanics of the spike. This may help to further explain the reasons for differences in technique between the indoor and outdoor spike approach and take off.
5. Studies need to also be conducted on males and not only females in order to generalize the results to a larger population of skilled volleyball players.
6. Acceleration data and ground reaction force data could be included in future studies to further explain the effects of different variables such as trunk extension on the outcome of the jump.

Coaching Recommendations

As the sport of beach volleyball continues to grow, the development of coaches and the need for technical instruction of players will further emerge. In order to help increase coaches' ability to train the outdoor volleyball spike, some recommendations regarding the outdoor approach, and take-off have been made:

1. A slower approach phase should be practiced in the outdoor spike approach in order to limit the amount of forward momentum of the athlete, since it cannot be decreased due to the lack of resistance force generated by the sand surface. This slower speed is relative to the softness of the sand. The harder the surface, the faster the approach. A slower approach will mean that the athlete needs to begin the approach earlier to provide enough time to plant, and take-off to contact the ball at the peak height of the jump.
2. Outdoor players demonstrate a slower transition from plant to take-off. This indicates that outdoor players need to enter the plant phase earlier to achieve a solid base of support between the feet and the sand surface. This is necessary to adapt to the displacement of the sand as the sand is packed down by the feet. Caution should be taken to ensure that the approach does not begin too early as this will force the athlete to slow down through the plant and take-off. This is not efficient because it eliminates the advantage of the stretch-shortening cycle and may decrease peak angular velocities at the trunk, hip, knee, and ankle joints.
3. The center of gravity should be gradually lowered during the early steps of the approach so that it is near its lowest point at initial foot plant. This will reduce the amount of downward momentum of the athlete at plant and decrease the transition time from plant to take-off.
4. A fast step close should be used, as it was found to be the most important contributor to increasing jump height in both the indoor and outdoor spike. A faster step close in beach volleyball also allows for greater braking forces to slow the horizontal velocity of the hitter. With both feet in contact with the ground, a

greater amount of horizontal ground reaction force can be sustained than if only one foot absorbs the force. In order to speed up the step-close, the athlete needs to use the airborne time of the long last step to bring the trailing leg forward closer to the front foot. This is done by flexing at the knee and driving the knee forward using hip flexion. If this is performed properly, the foot of the trailing leg should be right beside the front foot when it plants initially. Footwork and agility drills such as ladder drills can help the coach to train this skill.

5. Proper movements of the upper extremities and trunk should be encouraged in order to enhance the kinematics of the lower body and to raise the center of mass to higher heights at take-off. Large ranges of motion of shoulder flexion, producing a big arm swing, and trunk extension are required to place the extensor muscles of the hips and knees on a pre-stretch that otherwise cannot be achieved as efficiently during the plant do to the lack of resistance from the sand.
6. At the instant of take-off, horizontal velocity should be discouraged as it will decrease jump height. All forces at take-off should be directed vertically. Horizontal velocity and therefore drift does not provide the same advantages in beach volleyball as it does in the indoor game where it acts to increase the linear velocity of the hand at contact. In beach volleyball, strategy of the sport does not require the same force at contact and a higher contact point may be more advantageous as it provides the hitter more time for decision making and a greater area of court surface to hit at.
7. Strength training recommendations more specific to the sport of beach volleyball are to develop strong core strength, targeting all the intrinsic muscles within the

legs and trunk that are necessary for maintaining balance and reacting to the unpredictable sand surface. Other target areas should include the extensors of the trunk to increase the vertical acceleration of the trunk by reaching higher peak angular velocities of trunk extension; and shoulder flexors in order to increase the velocity of the upward arm swing (often neglected as the hitting action in volleyball requires the opposite movement of shoulder extension).

(Note: these are additional recommendations to the training specific to indoor volleyball).

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APPENDIX A

ETHICS APPROVAL

UNIVERSITY
OF MANITOBA

RESEARCH SERVICES &
PROGRAMS
Office of the Vice-President (Research)

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Winnipeg, MB R3T 5V6
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www.umanitoba.ca/research

APPROVAL FOR SERVICES

24 February 2004

TO: **Marion Alexander**
Faculty of Physical Education

FROM: **Stan Straw, Chair**
Education/Nursing Research ~~Ethics/Board~~ (ENREB)

Re: **Approval for Services to Elite Canadian and Manitoba Athletes**

Film Analysis of the Skills of Elite Canadian and Manitoba Athletes has been approved for 2004.

APPENDIX B

INFORMED CONSENT FORMS

Guidelines for Informed Consent

Research Project Title: A Biomechanical Analysis of the Skills of Elite Athletes in the Sport of Volleyball & A Biomechanical Comparison of the Indoor and Outdoor Volleyball Spike Approaches: How the Sand Surface Changes the Mechanics.
Researcher(s): Marion J.L. Alexander, professor, Adrian Honish, graduate student, Faculty of Physical Education and Recreation Studies

Sponsor (if applicable): Canadian Sport Center- Manitoba

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

Outline of the Study:

There are two main purposes of this study: to examine the techniques of the members of the Canadian Women's Volleyball Team, in order to assist coaches in improving their skill level; and to provide data that will be used in a masters thesis study focusing on the biomechanical differences between the indoor and outdoor spike approaches.

Methodology:

You will be filmed, likely on one occasion only, while practicing at your local practice facility, the Investors Group Athletic Centre, using filming equipment from the Biomechanics Laboratory in the Faculty of Physical Education. All practices are organized and administered by the National Team coach, who will instruct you regarding the skills to perform. Prior to filming you, the filming procedures will be explained. You will be asked to perform the skills as you normally would in a game situation, and your techniques will be filmed. You must provide informed consent for the study prior to filming. All filming procedures will be organized and administered by the principal investigators, Dr. Marion Alexander and Adrian Honish who will be assisted by other qualified graduate students.

Three video cameras will be used to film the athletes: one placed at the side of the athlete, one placed to the rear of the athlete at a safe distance from the players, and one placed overhead from behind the athlete to capture a view of hand contact on the ball. Two of the video cameras will be Gen-locked together to ensure that they start and stop at the same instant, so that three dimensional film data may be derived from the two cameras. The coach will instruct you regarding which skills are to be performed while the cameras are filming. The cameras will continue to film you until all of the skills of interest have been performed

When filming is completed, the films will be analyzed by the principal investigator and the graduate students working on the project. The types and ranges of motion in each of the skills, as well as selected linear and angular velocities in each of the skills will be described. An overall evaluation of the technique of each skill for each athlete will be provided to the coaches, and this will be provided in an oral session with the coaches and possibly the athletes, as well as in a written submission to the coaches. It is possible that some of the technique descriptions developed from this analysis may eventually be published in a technical journal in the sport being examined.

Risk:

There is no additional risk involved in this study, as you will perform the skills as you would normally perform them in a practice situation. The cameras will be out of the way, and will not interfere in any way with your performance of the skills.

Confidentiality:

The film will be viewed only by the researchers involved in the study, the coaches, and by the athletes in the study. The amount of data available to the athletes will be determined by the coaches. The data derived from the film will be available to the coaches and athletes in order to help to improve performance. The video films and all of the research data will be kept in a locked cabinet in the Biomechanics laboratory, and will not be used for any other purpose than the current study. No one will have access to the films or data except the principal investigator and the research assistants. After the project is completed the films and the data will be destroyed. It is possible that the technique analysis data will be published in a technical journal, however the identity of all subjects in the study will be kept confidential.

Signature:

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

Principal Researcher: Marion J.L. Alexander, Professor, Faculty of Physical Education and Recreation Studies, Ph 474 8642

This research has been approved by the Education/Nursing Research Ethics Board. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Secretariat at 474-7122. A copy of this consent form has been given to you to keep for your records and reference.

____
Participant's Signature Date

____
Researcher and/or Delegate's Signature Date

Guidelines for Informed Consent

Research Project Title: A Biomechanical Comparison of the Indoor and Outdoor Volleyball Spike Approaches: How the Sand Surface Changes the Mechanics
Researcher(s): Adrian Honish, BESS and Advisor: Marion J.L. Alexander, professor, Faculty of Physical Education and Recreation Studies

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

Outline of the Study:

The purpose of this study is to examine the techniques of elite indoor and outdoor volleyball players performing the spike approach in their designated sport (Indoor vs. Outdoor). The goal of the study is to identify the biomechanical differences between the indoor and outdoor spike approaches and what affect the sand surface has on them. Hopefully from this study one will be able to adapt easier to the sand surface and coaching implications can be made.

Methodology:

You will be filmed, likely on one occasion only, while practicing at your local indoor practice facility, or attending a the Canadian Open Beach Volleyball Championships at Wasaga Beach Ontario, Summer, 2004. You will be filmed using filming equipment from the Biomechanics Laboratory in the Faculty of Physical Education. All practices are organized and administered by the coach, who will instruct you regarding the skills to perform. Prior to filming you, the filming procedures will be explained. You will be asked to perform the skills as you normally would in a game situation, and your techniques will be filmed. You must provide informed consent for the study prior to filming. All filming procedures will be organized and administered by the principal investigator, Dr. Marion Alexander, who will be assisted by qualified graduate students.

Two video cameras will be used to film the athletes: one placed at the side of the athlete, and one placed to the rear of the athlete at a safe distance from the players. The video cameras will be Genlocked together to ensure that they start and stop at the same instant, so that three dimensional film data may be derived from the two cameras. The coach will instruct you regarding which skills are to be performed while the cameras are filming. The cameras will continue to film you until all of the skills of interest have been performed

When filming is completed, the films will be analyzed by the principal investigator and the graduate students working on the project. The types and ranges of motion in each of the skills, as well as selected linear and angular velocities in each of the skills will be described. An overall evaluation of the technique of each skill for each athlete will be provided to the coaches, and this will be provided in an oral session with the coaches and possibly the athletes, as well as in a written submission to the coaches. It is possible that some of the technique descriptions developed from this analysis may eventually be published in a technical journal in the sport being examined.

Risk:

There is no additional risk involved in this study, as you will perform the skills as you would normally perform them in a practice situation. The cameras will be out of the way, and will not interfere in any way with your performance of the skills.

Confidentiality:

The film will be viewed only by the researchers involved in the study, the coaches, and by the athletes in the study. The amount of data available to the athletes will be determined by the coaches. The data derived from the film will be available to the coaches and athletes in order to help to improve performance. The video films and all of the research data will be kept in a locked cabinet in the Biomechanics laboratory, and will not be used for any other purpose than the current study. No one will have access to the films or data except the principal investigator and the research assistants. After the project is completed the films and the data will be destroyed. It is possible that the technique analysis data will be published in a technical journal, however the identity of all subjects in the study will be kept confidential.

Signature:

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

Principal Researcher: Adrian Honish, BESS, Graduate student at the University of Manitoba. Advisor: Marion J.L. Alexander, Professor, Faculty of Physical Education and Recreation Studies, Ph 474 8642

This research has been approved by the Education/Nursing Research Ethics Board. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Secretariat at 474-7122. A copy of this consent form has been given to you to keep for your records and reference.

Participant's Signature Date

Researcher and/or Delegate's Signature Date

APPENDIX C

PILOT STUDY

PILOT STUDY

INTRODUCTION

The purpose of the pilot study was: to determine if the camera set-up described in the protocol of Chapter 3 would be optimal for data collection, to ensure that data could be collected accurately using the Peak5 Performance System, and to identify any key differences between the indoor and outdoor spike approaches that should be considered in this study.

The pilot study was conducted on two separate occasions. The outdoor spike approach was filmed at the Melrose Community Center in Winnipeg, Manitoba on July 1, 2004 while the Indoor spike approach was filmed July 16, 2004 at the Investors Group Athletic Center at the University of Manitoba.

METHODS

SUBJECTS

A single subject was recruited for this study from the 2004 Manitoba 18 and Under Women's provincial volleyball team. The subject had 6 years of competitive indoor volleyball experience competing at the high school, provincial team, and youth National team levels. She has also competed in the sport of beach volleyball for the past 2 years at a recreational level. The subject's characteristics are outlined in Table C-1.

Table C-1: Subject Characteristics

SUBJECT	SEX (M/F)	AGE (years)	HEIGHT (cm)	WEIGHT (kg)
1	F	18	172.5	61.36

PROTOCOL

WARM-UP

In order to prevent any risk of injury to the subject, the subject was told to ensure that they were properly warmed up prior to testing. The warm-up consisted of 5 minutes of light jogging around the outside of the gymnasium followed by 5 minutes of stretching that focused mostly on the muscles of the lower body and shoulders. The subject then performed five spike approaches without a volleyball and then five more approaches hitting a ball. Once this warm-up was complete, the athlete was requested to drink some water and take a five minute break while the cameras were turned on and the calibration tree was filmed.

FILMING TECHNIQUE

Two analog cameras were used to videotape the athlete. Camera 1 was a Panasonic Digital 5100 and camera 2 was a Panasonic OmniMovie HQ each of which was filming at a speed of 30 Hz or 30 frames per second. The cameras were set up at equal distances from the athlete and at 90-degree angles to each other.

Camera 1 (Panasonic OmniMovie HQ) was situated on a tripod in such a way that it captured an almost purely sagittal view of the athlete's right side. This was to help ensure accurate measurements of joint angles and velocities later on during analysis. Camera 2 (Panasonic Digital 5100) was be placed on a tripod perpendicular to camera 1 in order to capture a rear view of the athlete that was later used for three-dimensional analysis using the Peak 5 Performance System. Each camera was manually focused with a shutter speed of 1/1000 to ensure that no blurring of the image would occur.

Both cameras were genlocked together to ensure precise synchronization of the filming rate and timing of both cameras. The genlock system ensures that each field captured by camera 1 starts and ends at precisely the same time as the same field captured by camera 2. A staggering of fields as small as 1/120 Hz can result in inaccurate calculations during data collection. A time code generator was also hooked up into the audio ports of each camera. This was used to apply time code (an audio signal) to both cameras, which would later be recognized by the Peak5 Technologies System during digitization.

Following the set-up of the cameras and prior to filming the athlete, the two cameras were calibrated using a calibration tree from Peak Technologies. The calibration tree was assembled and placed in position at the net where the ball would be contacted. The diameter of the tree was large enough to span the area of the final step of the approach all the way through contact and landing allowing for accurate calculations throughout all key positions of the approach.

EXPERIMENTAL PROCEDURE

The subject was filmed on two separate occasions, once on a sand volleyball court, and a second time on an indoor wooden surface court. It should be noted that the depth of sand on the outdoor court was only 28 cm, which is 12 cm less than the regulation depth set in the rules of the FIVB. For each condition, the subject was asked to hit five balls consecutively with a brief rest between trials and to approach and hit the ball, as she would do so in a game. The ball was tossed by an experienced coach to ensure consistency in the set and the ball was to be hit into the cross-court position of the court in order to control for any variability between different types of hit (i.e. line versus cross-court). The target area for hitting was position 5 on the opposing court. Only balls landing in that area were considered for video-analysis.

VIDEO ANALYSIS

Video analysis was used to gather quantitative information regarding the biomechanics of the indoor and outdoor spike approaches. This video analysis was conducted using the Peak5 software from the Peak Performance Technologies (1994) video motion analysis system.

First, a spatial model or 14-segment computer representation of a female volleyball player was created. The model consisted of 21 individual points forming the 14 segments. The center of mass of each segment was also used by Peak to determine the center of mass of the system at any given moment in the skill. It was important to ensure that each of the 21 digitized points could be seen in at least one of the camera views at all times. From this, the Peak5 software was able to interpolate all of the points accurately. This was not a problem and the volume of error in the digitizing process was kept to a minimum, as determined by the Peak5 system.

Only a single indoor and outdoor approach was digitized for video analysis. The trial selected was the one that yielded the highest jump height, which was estimated by a frame by frame observation on a computer screen. This trial was entered into the Peak system for further analysis and several variables were measured and used for comparison between the indoor and outdoor spike approaches. The first and most important key variable studied was the peak vertical displacement of the center of mass. This was used as the key indicator of jump performance and showed whether or not differences were significant between the indoor and outdoor spike approaches.

After jump height was determined, several variables affecting jump performance were measured using the Peak system. These included:

- the path of the center of mass through the approach phase prior to foot plant
- horizontal and vertical velocities of the center of mass, including the effectiveness of decreasing horizontal momentum during the plant phase
- angular displacements and velocities at the hip, knee, and ankle joints during the plant and take-off phases
- shoulder angular displacements and velocities throughout the entire approach
- the timing of each of these events and how they relate to one another.

One of the purposes of this study was to show that the Peak5 motion analysis software could be used to determine these quantitative values accurately. This was accomplished and comparisons could be made between values found in the indoor and outdoor spike approaches.

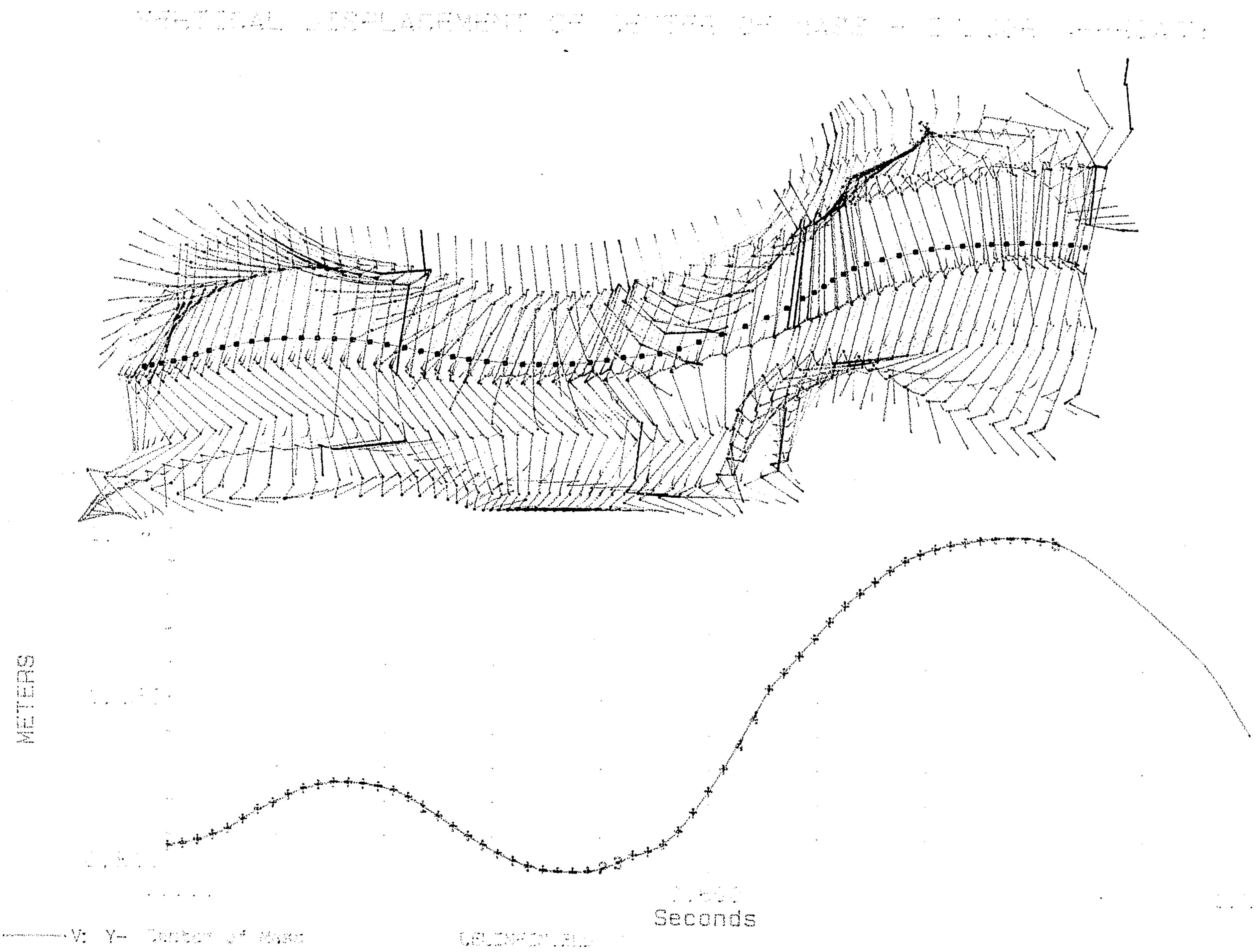
RESULTS

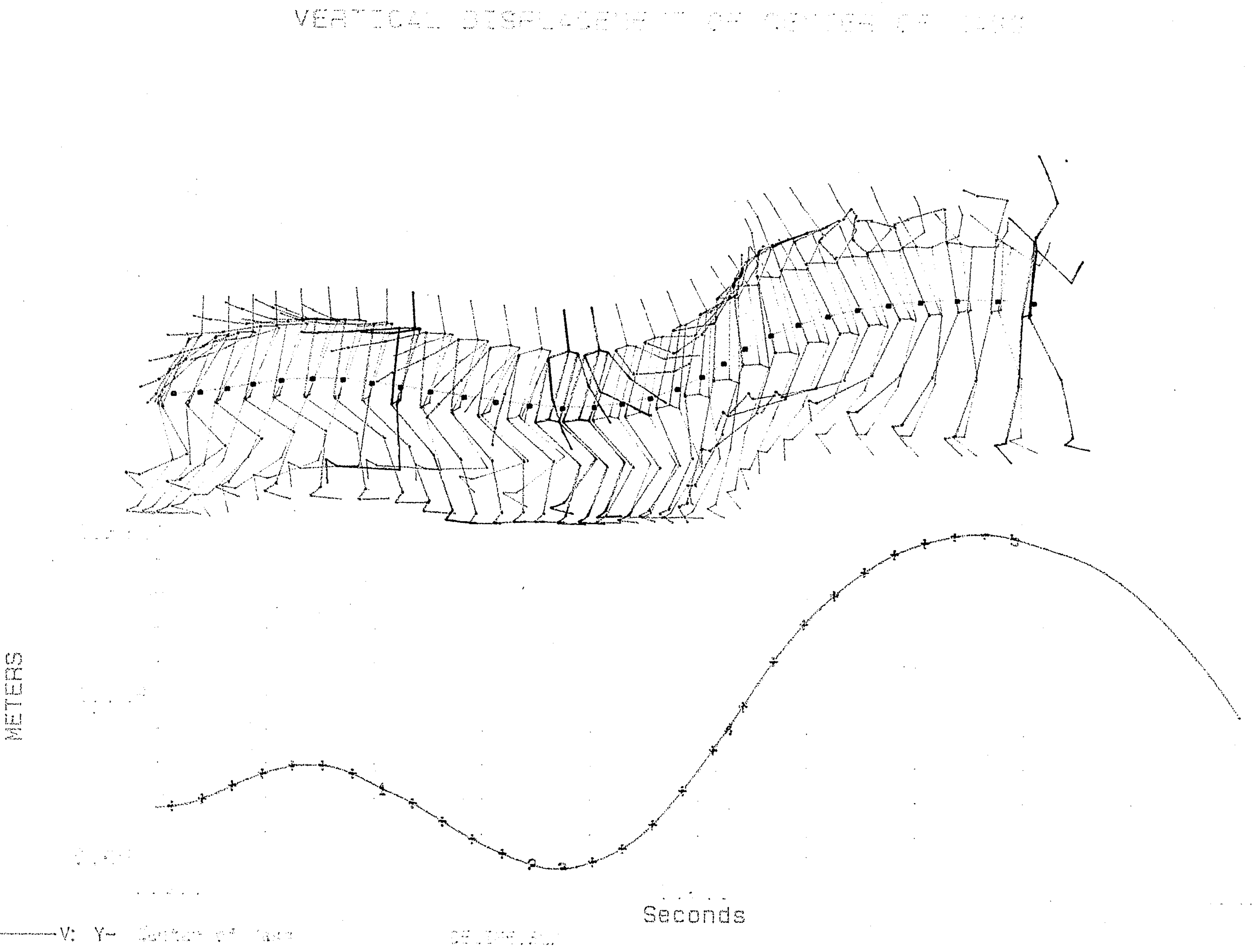
When comparing the indoor volleyball spike approach to the beach volleyball spike approach, performed on almost thirty centimeters of sand, it was found that there were several similarities and few key differences in their mechanics.

Jump performance was determined by the maximum height that the center of gravity reached while airborne. On the indoor court, the subject's center of mass reached 1.50m from the ground and she contacted the ball with her hand 2.53m above the ground, whereas jumping off the sand allowed her center of mass to reach only 1.38m and she contacted the ball at a much lower 2.37m from the ground. Therefore, her height of contact was 16.1cm lower when jumping off the sand surface.

The path of the center of mass throughout the entire approach was determined for both the indoor and outdoor approaches and is plotted in Figures C-1 and C-2 respectively as the vertical displacement of the center of mass. The paths shown for the center of mass are nearly identical in both situations, however, the height of the center of mass was found to be consistently higher in the indoor condition. Most interestingly, at take-off the subject was able to raise her center of gravity to a position 1.13m off the ground during the indoor approach compared to 1.01m during the outdoor approach. As will be discussed later, this is largely due to a more efficient use of the arm swing throughout the approach and at take-off.

The peak horizontal and vertical velocities of the center of mass along with horizontal and vertical velocities at key positions were also determined for the spike approach under both conditions. Horizontal velocities were measured immediately prior to and after initial and second foot contacts and then again at take-off in order to predict


VERTICAL DISPLACEMENT OF CENTER OF MASS -
METERS
Seconds
V: Y- Center of Mass


VERTICAL DISPLACEMENT OF CENTER OF MASS
METERS
Seconds
V: Y- Center of Mass

the effectiveness of braking forces generated during the plant phase as the athlete tries to decrease horizontal momentum. Vertical velocities were calculated at the same key events, and were used to compare the downward force that the body has to overcome during the plant phase and then the upward velocity of the center of mass at take-off which is the key contributor to the height of the jump. This information is clearly presented in Table C-2.

Table C-2: Horizontal and vertical velocities of the center of mass during key positions of the indoor and outdoor spike approaches.

	INDOOR	**OUTDOOR**
HORIZONTAL VELOCITY OF CENTER OF MASS		
• Prior to Initial Foot Plant	3.109m/s	2.647m/s
• After Initial Foot Plant	2.971m/s	2.403m/s
• Prior to Second Foot Plant	2.320m/s	2.099m/s
• After Second Foot Plant	2.156m/s	1.829m/s
• At Take-Off	1.567m/s	1.532m/s
VERTICAL VELOCITY OF CENTER OF MASS		
• Initial Foot Plant	-1.208m/s	-0.906m/s
• Second Foot Plant	0.787m/s	0.468m/s
• Take-Off	3.307m/s	2.940m/s

The subject demonstrated a greater amount of horizontal velocity early in the indoor approach but then was able to decrease this velocity through a more efficient braking phase during the plant. From initial foot plant to take-off the subject was able to decrease her horizontal velocity by almost 50% in the indoor condition versus 42% on the sand. A few reasons for this are: firstly that her last step into the plant was 0.32m longer for the indoor approach (1.41m vs. 1.09m) and 0.12m higher (0.99m vs. 0.87m). Secondly, she planted her foot 0.09m further ahead of her center of mass for the indoor condition (0.39m in front vs. 0.30m). This longer step increases the magnitude of the horizontal component of the ground reaction force pushing back on the athlete.

The key concern of any athlete who wants to maximize jump height is to increase his or her vertical velocity at take-off. At take-off the subject's center of mass reached a vertical velocity of 3.31m/s indoors versus 2.94m/s outdoors. Both of these values were the highest recorded vertical velocity occurring precisely at take-off. This is important as it is a common error for the peak vertical velocity of the center of mass to occur slightly before take-off as opposed to at take-off. Vertical velocity is affected by the quality of muscle contraction in the legs and trunk as they begin to extend, and by the effectiveness of the athlete's armswing through take-off.

Table C-2 shows the vertical velocity of the subject under both conditions. For the indoor spike approach, at initial foot contact, the subject's center of mass was moving downward at a rate of -1.21m/s and began to decelerate immediately afterwards until 0.15seconds later when it began to move upward at a rate of 0.03m/s. By the time the athlete's second foot contacted the ground, she was already moving upward at a velocity of 0.79m/s. This is equal to a change of velocity of 2 m/s in a time of 0.2 seconds. In order to maximize jump performance, athletes need to perform this change from downward to upward momentum as fast as possible. This will yield the largest impulse and therefore the greatest amount of force that is produced. In this case, impulse is equal to the change in momentum or 122.42 N•s and therefore, it can be calculated that 612.1N of force was produced to perform this action (Force x Time = Impulse).

For the outdoor spike approach, the athlete entered the initial foot contact with a downward velocity of his center of mass of –0.91m/s. Her downward velocity continued to increase at an average rate of 5 m/s^2 for the next 0.05 seconds before beginning to decrease. Therefore, she contacted the ground with a downward velocity of –0.91m/s, but reached a peak downward velocity 0.05 seconds later of 1.15m/s. It took her 0.03 seconds longer to reach a positive vertical velocity than it did for the indoor spike approach. By the time she reached second foot contact, she was only able to increase the upward velocity of her center of mass to 0.47m/s (0.32m/s slower than the indoor approach). Therefore the impulse applied on the athlete alone was considerably lower than that of the indoor approach at 84.31 and she only generated 421.57 N of force to produce the change in momentum. Part of the reason for this is that much of the athlete's downward momentum and the impulse required to change her momentum was taken up by the movement of the sand in the opposite direction.

The ability to change this downward velocity to upward velocity relies largely on the contractions occurring at the hip, knee and ankle joints from initial foot contact through take-off. Table C-3 shows the ranges of motion at the hip, knee and ankle joints from peak flexion occurring during the crouch position of the plant phase to take-off and compares them between the indoor and outdoor spike approaches.

Table C-3: Angular displacement at the knee, hip, and ankle joints for both the indoor and outdoor spike approaches. Angles measured at point of peak flexion during the crouch of the plant phase and at the instant of take-off.

JOINT	**INDOOR**		**OUTDOOR**	
	PEAK FLEXION	*@ TAKE-OFF*	*PEAK FLEXION*	*@ TAKE-OFF*
Rt. Knee	108.902°	174.9°	106.06°	173.36°
Lt. Knee	126.170°	166.693°	111.228°	171.871°
Rt. Hip	114.626°	174.047°	113.126°	170.604°
Lt. Hip	118.705°	168.971°	117.218°	168.279°
Rt. Ankle	37.4° of dorsi flexion	34.8° of plantar flexion	31.1° of dorsi flexion	47.6° of plantar flexion
Lt. Ankle	25.3° of dorsi flexion	27.5° of plantar flexion	35.1° of dorsi flexion	30.5° of plantar flexion

The angular displacements measured at each joint of the lower body are very similar between the indoor and outdoor spike approaches. No significant differences were found except for a greater amount of plantar flexion in both the right and left ankles at take-off for the outdoor condition. This is likely due to the softer sand surface and the tendency for the toes to sink deeper in the sand as the weight shifts forward and the ankles begin to planter flex. Therefore, resulting in less resistance to plantar flexion and a greater range of motion overall.

Angular velocities at the hip, knee and ankle joints were also calculated and are displayed in Figures C-3 and C-4 for the indoor and outdoor conditions respectively. An interesting finding was that although peak angular velocities occurring at the right hip, knee, and ankle were similar between surfaces, the peak angular velocities for the left hip, knee, and ankle were found to be significantly higher when jumping from the sand surface. The outdoor spike condition yielded 203 degrees/s, 92 degrees/s and 242 degrees/s greater angular velocity at the left knee, hip and ankle respectively. A possible explanation for this is that the same instant that the second foot plants (left foot), the left leg begins to extend immediately and there is no absorption phase such as that seen when the right foot plants initially. At initial foot plant, the right leg flexes gradually at the hip and knee, while the ankle dorsi flexes in order to decrease downward momentum and prepare for force production. Therefore, the left foot is planted on top of the fresh sand and any initial force production will result in the foot sinking deeper into the sand. Because the sand surface does not provide as much resistance to extension of the leg, the leg is able to extend much faster with any given amount of force production.

The armswing throughout the approach plays a critical role in increasing ground reaction forces at take-off by raising the center of gravity rapidly prior to take-off and therefore increasing the reaction force that pushes downward on the ground. The subject

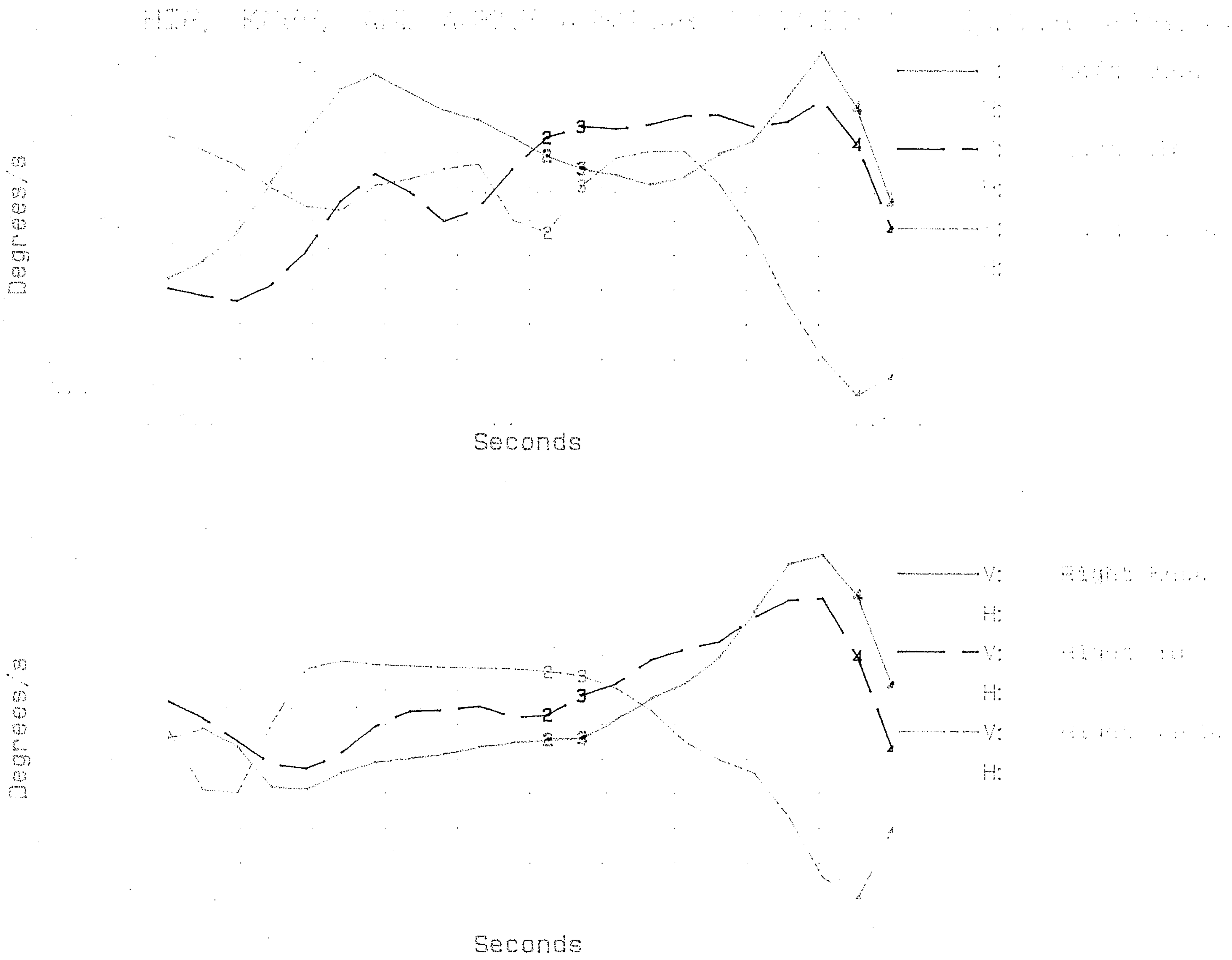

Degrees/s
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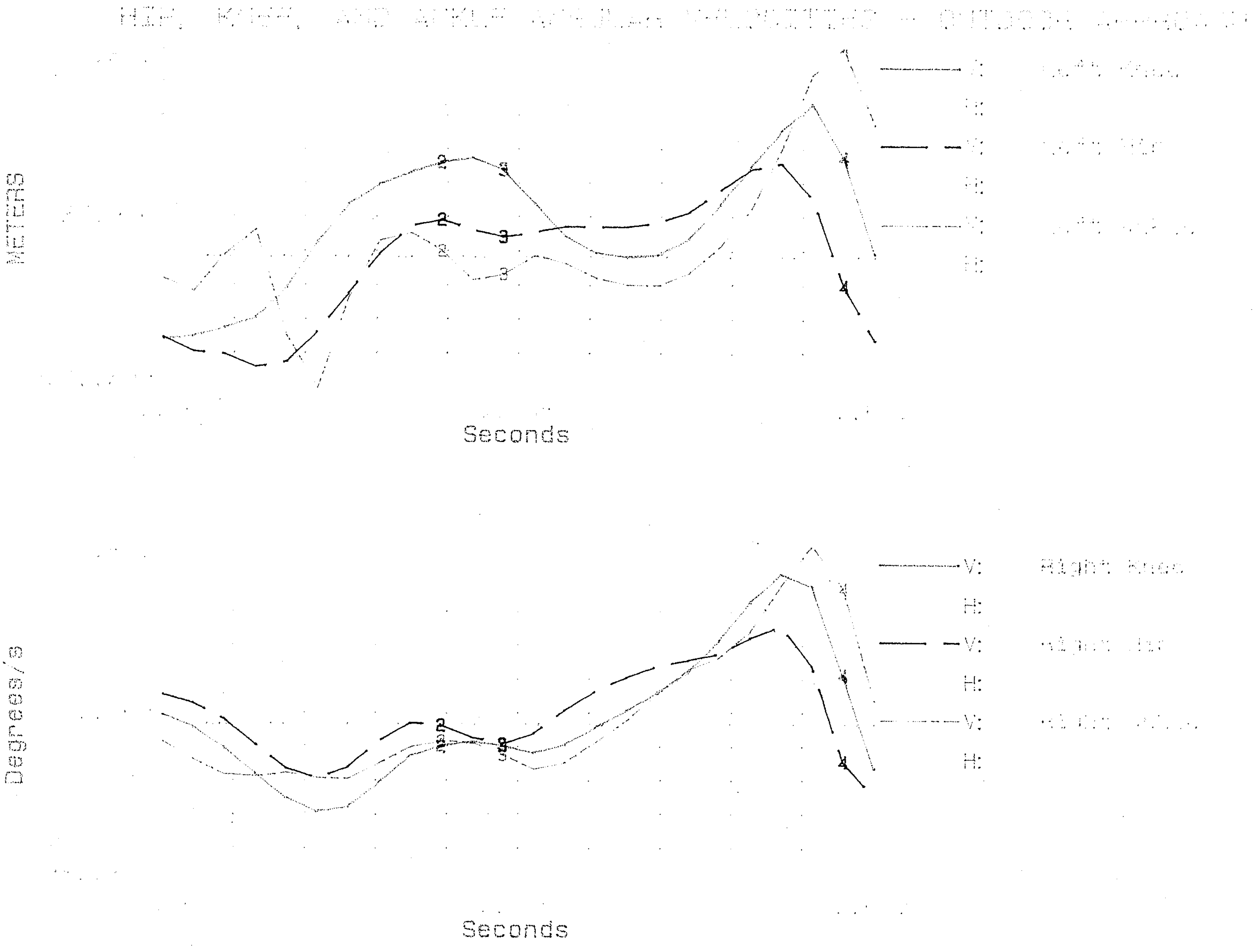
Figure C-3


METERS
Seconds
V:
H:
V:
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V:
H:
Degrees/s
Seconds
V: Right Knee
H:
V: Right Hip
H:
V: Right Ankle
H:

Figure C-4

in this study demonstrated a much larger range of motion in her armswing during the indoor spike approach (shown in Table C-4). This was entirely due to a much larger range of shoulder hyperextension behind the body. Shoulder hyperextension likely resulted from a longer last step that allowed for a greater amount of time to bring the arms back as well as a higher horizontal velocity during the approach. Due to the inertial lag of the arms (their resistance to movement) they are left behind the body as the trunk moves forward.

Table C-4: Angular displacement of the right (Rt.) and left (Lt.) shoulder joints at the position of maximum hyperextension behind the body during the last step and at full flexion at take-off. Measured for both the indoor and outdoor spike conditions.

	INDOOR		OUTDOOR	
JOINT	HYPEREXTENSION	FLEXION @ TAKE-OFF	HYPEREXTENSION	FLEXION @ TAKE-OFF
Rt. Shoulder	104.657°	125.68°	81.88°	126.662°
Lt. Shoulder	89.039°	151.78°	78.155°	151.981°

Shoulder angular velocities were also determined for the key positions of maximum knee flexion in the crouch and take-off. It was found that higher peak angular velocities were present during shoulder flexion in the outdoor approach and they occurred immediately prior to the point of maximal knee flexion (799.38°/s vs. 696.69°/s in the right shoulder). However, at take-off, the indoor spike demonstrated significantly higher angular velocities at the shoulder joint (155.74°/s vs. –52.85°/s). This means that the arms were still driving upward at take-off and therefore acting to raise the center of mass, whereas a negative value for shoulder flexion in the outdoor spike condition indicates that the shoulder was actually extending at the instant of take-off. This likely accounts in part for the higher vertical velocity of the center of mass at take-off in the indoor spike approach. To further illustrate this point, the linear velocity of the right and left elbows was calculated in the Y-direction. It was found that the under the indoor conditions, the right and left elbow joints were lifted through take-off at much higher velocities (4.82m/s vs. 2.93m/s for the right elbow, and 3.57m/s vs. 2.99m/s for the left. Any upward movement that acts to accelerate the center of mass upward will result in increased ground reaction forces that push the athlete up and cause her to jump higher.

DISCUSSION

Clear differences occurred between the indoor and outdoor spike approaches. This study was a pilot study with the goal to recognize a need for more in-depth biomechanical comparisons between the two skills and to show that data could accurately be measured using the Peak5 software from Peak Technologies (1994). The results showed a significant decline in peak jump height when performing the spike approach on the sand surface of the outdoor court. With the sand surface being the only independent variable in the study, it clearly has an effect on the mechanics of the spike approach that results in an inability to jump as high as one could on an indoor wood surface.

The sand surface provides a much smaller resistance to any forces applied to it. When the athlete begins force production to jump and begins to extend at the hips and knees, while plantar flexing the ankles, the sand surface does not provide an equal and opposite push back on the athlete. Instead, the sand absorbs a significant amount of this force by compressing and dispersing in all directions so that the athlete's foot sinks deeper into the sand. When performing on a wooden court surface, there is very little give to the floor surface and almost a pure return of force from pushing down on the ground to the ground pushing back up with an equal and opposite force. As a result of this, the athlete is not able to decrease downward momentum as quickly after the foot plants, and continues to accelerate downward for a short period of time before the downward momentum can be decreased and upward momentum generated. This results in a much smaller impulse, as the transition from negative to positive work requires a longer time delay.

During the outdoor approach, the subject also showed a slower horizontal velocity as she entered into the plant phase. This horizontal velocity, combined with the associated braking forces is important as it acts to load the quadriceps and glutes in an eccentric contraction or pre-stretch that stiffens the knee and hip joints and stores energy in the series elastic component of the muscles. This energy can later be released to provide a more forceful concentric contraction.

Finally, the armswing is a critical component to increasing the height and velocity of the center of mass at take-off. All athletes who wish to jump to some peak height need to maximize the height of their center of mass at take-off and this is done by driving all possible body parts upward, including the arms. The subject in this study demonstrated significantly higher shoulder angular velocities and linear velocities of the elbows at take-off during the indoor spike approach. This forces the center of gravity to raise upward through take-off at a much higher velocity and therefore, also increases ground reaction forces on the ground.

The Peak5 software proved to be accurate when measuring the data necessary for this study. One of the only problems found is the difficulty in digitizing the toes and heels of athletes performing in the sand. For the duration of the plant phase, the toes and heels are constantly raising and lowering in the sand and are lost from sight when buried. This makes the digitizing procedure difficult and less accurate. More precise care will need to be taken when digitizing the feet of the subjects while in the sand. This may allow the amount of linear displacement of the toes to be accurately calculated in order to quantify the exact amount that the toes are driven deeper into the sand during force production.

APPENDIX D

SUBJECT CHARACTERISTICS

SUBJECT CHARACTERISTICS

SUBJECT	VARIABLES		
INDOOR	AGE	HEIGHT (cm)	WEIGHT (kg)
1	22	187	73.18
2	23	185.4	68.18
3	19	187	77
4	18	175.3	66.9
5	24	178	78
6	25	194	73.5
7	19	174	60.57
8	18	187	70.38
9	22	186.5	76.36
10	21	175	72.72
Mean	**21.1**	**182.92**	**71.679**
OUTDOOR			
1	42	176	65
2	23	168	61.36
3	23	173	68.18
4	22	170	59.09
5	36	175	71
6	22	170	58.18
7	18	185	80
8	21	183	68.18
9	28	171	63.64
10	36	170.18	72.73
Mean	**27.1**	**174.118**	**66.736**

APPENDIX E

RAW DATA:

INDOOR SUBJECT GROUP

INDOOR APPROACH PHASE

	VARIABLES							
	C of M Hv		C of M Vv		Last Step		Peak Shoulder Hyperextension	
SUBJECT	Prior to last step	at take off	Prior to last step	at take off	Length of Last Step	Height of C of M	Right Shoulder	Left Shoulder
1	3.541	0.675	-1.222	3.728	1.451	0.917	101.660	122.624
2	3.680	1.987	-0.605	3.236	1.355	1.021	71.877	61.437
3	3.165	1.796	-0.745	2.664	1.181	0.919	90.702	103.956
4	3.133	1.469	-1.052	2.710	1.000	1.063	104.657	89.039
5	3.700	2.649	-0.612	2.515	1.287	1.049	74.783	102.426
6	2.939	1.032	-0.058	2.912	1.612	0.918	77.318	67.794
7	3.666	1.609	-0.789	2.936	1.491	0.784	74.442	60.935
8	3.090	2.087	-0.398	2.660	1.059	0.860	61.357	57.753
9	3.345	2.167	-0.610	2.466	1.372	1.001	98.753	93.946
10	2.969	1.347	-0.512	2.402	1.139	1.065	80.387	71.744
mean	**3.323**	**1.682**	**-0.660**	**2.823**	**1.295**	**0.960**	**83.594**	**83.165**
Std. Dev.	**0.302**	**0.338**	**0.326**	**0.459**	**0.198**	**0.095**	**14.490**	**22.335**

INDOOR PLANT PHASE

	VARIABLES								
SUBJECT	Position of C of M @ Initial Foot Plant (m)	Step Close Time (sec)	Time of Plant & Take-Off	Peak Angular Displacements (flexion) Hip	Knee	Ankle (dorsi flexion)	Trunk	Angular Velocities Trunk	Shoulder
1	0.423	0.100	0.250	108.460	102.050	26.700	17.750	330.750	882.470
2	0.404	0.183	0.350	104.200	107.630	23.990	21.470	141.110	653.620
3	0.182	0.183	0.330	116.990	113.040	30.800	25.593	170.000	402.930
4	0.216	0.200	0.350	114.630	108.900	25.290	22.640	118.620	696.690
5	0.170	0.200	0.366	115.520	114.060	33.340	24.310	130.230	571.250
6	0.401	0.233	0.383	118.450	111.400	38.610	5.910	134.310	603.420
7	0.461	0.117	0.284	110.310	117.020	20.390	25.050	139.840	617.550
8	0.201	0.200	0.330	112.850	123.120	27.920	22.020	110.630	482.330
9	0.259	0.183	0.330	123.680	114.540	27.790	14.830	161.220	666.130
10	0.187	0.183	0.350	115.290	115.850	22.610	19.370	125.590	549.910
mean	**0.290**	**0.178**	**0.332**	**114.038**	**112.761**	**27.744**	**19.894**	**156.230**	**612.630**
Std. Dev.	**0.117**	**0.040**	**0.039**	**5.462**	**5.752**	**5.379**	**5.955**	**63.908**	**129.585**

INDOOR TAKE-OFF PHASE

VARIABLES												
SUBJECTS	Angular Displacements				Peak Angular Velocities				Vv of C of M	Hv of C of M	Height of Center of Mass	
	Hip	Knee	Ankle (plantar)	Trunk	Hip	Knee	Ankle	Trunk	(m/s)	(m/s)	Absolute (m)	Relative to Ht. (%)
1	168.830	162.900	32.560	-15.850	662.400	1147.710	1149.44	330.750	3.728	0.675	1.106	59.140
2	166.700	149.360	24.350	1.560	489.600	498.710	659.01	141.110	3.236	1.990	1.154	62.240
3	166.570	131.520	36.100	-11.060	341.490	208.100	418.99	161.000	2.675	1.796	1.105	56.200
4	-5.953	174.900	34.780	7.470	682.630	953.580	1154.60	118.620	2.710	1.469	1.158	66.070
5	152.480	134.110	17.230	-6.800	309.820	189.790	388.02	130.230	2.520	2.650	1.140	64.040
6	151.860	162.000	23.160	-17.110	387.850	647.620	855.13	134.310	2.912	1.032	1.171	60.360
7	-5.070	143.250	13.610	-7.870	487.530	283.620	356.76	132.180	2.936	1.609	1.059	60.860
8	-25.150	146.870	19.800	-11.130	320.990	194.400	345.86	98.160	2.660	2.087	1.217	65.080
9	-29.610	147.030	18.410	-11.940	367.970	301.170	413.29	161.220	2.466	2.167	1.150	61.660
10	166.200	146.920	15.480	-8.520	381.080	289.030	381.50	160.970	2.402	1.347	1.182	67.500
Mean	**90.686**	**149.886**	**23.548**	**-8.125**	**443.136**	**471.373**	**612.26**	**156.855**	**2.825**	**1.682**	**1.144**	**62.320**
Std. Dev.	**9.394**	**13.327**	**8.232**	**7.539**	**135.461**	**340.678**	**326.70**	**64.355**	**0.459**	**0.581**	**1.144**	**1.100**

INDOOR AIRBORNE PHASE

	VARIABLES			
SUBJECT	VerticalDisp of C of M (m)	Vertical Disp of Right Hip (m)	Height of Contact	Distance of Horizontal Drift (left toe take off to landing) (m)
1	0.649	0.715	2.736	0.840
2	0.459	0.517	2.550	1.290
3	0.471	0.486	2.304	1.106
4	0.350	0.386	2.530	0.712
5	0.444	0.482	2.314	1.554
6	0.438	0.471	2.458	1.677
7	0.569	0.648	2.364	1.019
8	0.450	0.494	2.412	1.550
9	0.377	0.429	2.297	1.280
10	0.374	0.445	2.344	0.817
Indoor	**0.458**	**0.507**	**2.431**	**1.185**
Std. Dev.	**0.091**	**0.044**	**0.141**	**0.341**

APPENDIX F

RAW DATA:

OUTDOOR SUBJECT GROUP

OUTDOOR APPROACH (Prior to Plant)

	VARIABLES							
	C of M Hv		C of M Vv		Last Step		Peak Shoulder Hyperextension	
SUBJECT	**Prior to last step**	**at take off**	**Prior to last step**	**at take off**	**Length of Last Step**	**Height of C of M**	**Right Shoulder**	**Left Shoulder**
1	2.897	0.929	-0.987	2.758	1.185	0.918	72.599	58.625
2	1.985	0.762	-1.339	2.607	0.903	0.932	74.285	71.527
3	3.007	0.718	-0.671	2.371	0.825	0.851	85.394	73.248
4	2.642	0.891	-0.854	2.427	0.962	0.845	80.115	95.239
5	2.659	1.051	-1.061	2.850	0.853	0.859	78.020	101.880
6	2.845	1.095	-0.590	3.040	1.028	0.846	97.067	96.186
7	2.484	0.699	-0.467	2.718	0.782	0.892	90.503	106.245
8	3.004	1.056	-0.804	2.355	1.245	0.814	75.431	93.385
9	3.090	0.779	-0.483	2.929	0.912	0.957	89.068	87.996
10	2.763	1.244	-1.152	2.835	1.161	0.946	75.222	91.450
mean	**2.738**	**0.922**	**-0.841**	**2.689**	**0.986**	**0.886**	**81.770**	**87.578**
Std. Dev.	**0.325**	**0.034**	**0.294**	**0.241**	**0.162**	**0.050**	**8.277**	**15.040**

OUTDOOR PLANT PHASE

	VARIABLES								
SUBJECT	Position of C of M @ Initial Foot Plant (m)	Step Close Time (sec)	Time of Plant & Take-Off	Peak Angular Displacements (flexion)				Angular Velocities	
				Hip	Knee	Ankle (dorsi flexion)	Trunk	Trunk	Shoulder
1	0.190	0.050	0.300	117.230	127.790	N/A	30.930	108.120	285.600
2	0.162	0.066	0.370	109.530	114.010		31.360	136.360	369.760
3	0.138	0.167	0.450	118.560	109.940		19.040	50.720	417.958
4	0.248	0.150	0.370	110.530	117.570		21.180	98.540	531.140
5	0.124	0.067	0.370	111.240	115.810		22.480	128.710	607.860
6	0.287	0.217	0.450	94.410	84.280		30.100	136.290	467.440
7	0.264	0.150	0.420	109.510	104.680		29.520	147.220	611.800
8	0.315	0.133	0.350	111.830	122.910		20.790	101.700	456.550
9	0.336	0.167	0.400	95.160	107.610		45.460	395.700	780.500
10	0.242	0.066	0.330	117.910	125.460		21.340	142.000	522.430
Mean	**0.231**	**0.123**	**0.381**	**109.591**	**113.006**		**27.220**	**144.536**	**505.104**
Std. Dev.	**0.074**	**0.057**	**0.049**	**8.533**	**12.625**		**8.021**	**93.909**	**140.093**

OUTDOOR TAKE-OFF PHASE

	VARIABLES											
SUBJECTS	Angular Displacements				Peak Angular Velocities				Vv of C of M	Hv of C of M	Position of C of M	
	Hip	Knee	Ankle (plantar)	Trunk	Hip	Knee	Ankle	Trunk	(m/s)	(m/s)	Absolute (m)	Relative to Ht. (%)
1	170.740	139.270	N/A	6.440	341.110	133.980	N/A	108.120	2.758	0.929	1.084	61.590
2	163.390	145.680		12.239	373.290	260.740		136.360	2.607	0.762	0.987	58.750
3	166.070	145.460		-7.700	376.870	279.350		50.720	2.371	0.718	1.046	60.460
4	170.100	159.510		-5.490	519.760	334.070		98.540	2.427	0.891	1.025	60.290
5	174.340	148.470		-2.990	451.670	338.530		128.710	2.850	1.051	1.124	61.230
6	166.400	151.960		-5.350	530.450	553.070		136.290	3.040	1.095	1.033	60.760
7	160.230	158.870		-4.530	429.610	472.570		102.880	2.718	0.699	1.126	60.860
8	166.380	158.390		-5.680	454.700	308.330		98.220	2.355	1.056	1.045	57.100
9	168.000	175.570		7.080	794.040	756.640		395.700	2.929	0.779	1.130	66.080
10	172.970	161.780		-1.690	427.800	329.420		142.000	2.835	1.244	0.998	58.640
mean	**167.862**	**154.496**		**-0.767**	**469.930**	**376.670**		**139.754**	**2.689**	**0.922**	**1.060**	**60.576**
Std. Dev.	**4.310**	**10.491**		**2.862**	**128.993**	**175.332**		**93.909**	**0.241**	**0.185**	**0.053**	**2.400**

OUTDOOR AIRBORNE PHASE

	VARIABLES			
SUBJECT	VerticalDisp of C of M (m)	Vertical Disp of Right Hip (m)	Height of Contact	Distance of Horizontal Drift (left toe take off to landing) (m)
1	0.444	0.473	2.239	0.910
2	0.442	0.466	2.181	0.612
3	0.340	0.400	2.099	0.489
4	0.360	0.388	2.300	0.737
5	0.405	0.458	2.300	0.693
6	0.410	0.514	2.233	0.978
7	0.406	0.448	2.483	0.520
8	0.325	0.388	2.067	0.871
9	0.412	0.403	2.427	0.792
10	0.454	0.478	2.222	0.950
Mean	**0.400**	**0.442**	**2.255**	**0.755**
Std. Dev.	**0.044**	**0.044**	**0.130**	**0.175**