AN ABSTRACT OF THE THESIS OF

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Title: Kinetic and Kinematic Analysis of Thai Boxing Roundhouse Kicks.

Abstract approved: ______________________________
Gerald A. Smith

The purpose of this study was to determine kinetic and kinematic characteristics of Thai Boxing Roundhouse Kicks. In order to measure the kinetic variables of peak force and impulse, a triaxial accelerometer was inserted into a kicking bag. The force data were derived from the known mass and measured acceleration of the kicking bag. Validation testing comparing applied forces to estimated forces based on accelerometers output showed this instrument provided accurate estimates of the force applied to the kicking bag (r = .99). The MacReflex motion analysis system was utilized with three cameras operating at 120 frames per second to obtain the kinematic characteristics of final linear velocity of the kicking ankle, linear velocity of the kicking ankle and knee, angular velocity of the knee, and the angular velocity of the shank and thigh projected onto the horizontal plane.

The subjects were ten male Thai Boxing performers with 8 to 48 months of training experience. The kicking trials were conducted at three height levels. It was hypothesized that the peak force, impulse, and the final linear velocity of the kicking ankle at impact would be greater for the lower level of kicks as compared to the higher level of kicks. It was also hypothesized that peak force and impulse would be positively related the subjects' leg strength. For the relationship between kinetic variables and kinematic variables it was hypothesized that peak force and impulse would be positively related to the final linear velocity of the kicking ankle.

In comparing the roundhouse kick at different height levels the middle level kick generated the greatest peak force and impulse, while the high level kick involved the least force and impulse. The amount of peak force and impulse were directly related to the final velocity of the ankle ($r = .86$, and $r = .79$ respectively), but they were not significantly related to the leg strength. This study found that the Thai Boxing roundhouse kick can easily generate enough force to cause neurological impairment, skull fractures, facial bone fractures, and rib fractures. These results suggest that there is a greater need for regulations protecting the competitors in Thai Boxing.

Kinetic and Kinematic Analysis of Thai Boxing Roundhouse Kicks

by

Suwat Sidthilaw

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Major Professor, representing Human Performance

Chair of Department of Exercise and Sport Science

Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Kinetic and Kinematic Analysis of Thai Boxing Roundhouse Kicks

Chapter 1
Introduction

Muay Thai, or Thai Boxing , is a unique martial art and a method of self-defense. It started in ancient times as a means of self-protection from the attacks of animals and enemies and has become one of the most popular individual sport programs in the world. In the past Thailand was a monarchy. The Thai kings strongly supported boxing and martial arts so that Thai Boxing became the most important sport in the country in addition to being a method of self defense. After the First World war when Thailand sent troops to fight with the Allies, Thai Boxing became widespread throughout both Asian and Western countries (Kraitus, 1988). Today Thai Boxing is known all over the world.

Thai Boxing rules are quite different from international boxing rules. A Thai Boxing match has five rounds of fighting with three minutes per round and two minutes rest between rounds. Thai Boxing allows the use of four offensive maneuvers: punches, elbow-strikes, knees-strokes, and a variety of kicks. These maneuvers may all be used to attack any part of the opponent's body.

Among the four attacking skills of Thai Boxing, the roundhouse kick is the most dangerous weapon with which to devastate the opponent (Young, 1991). The roundhouse kick can be kinematically broken down into four essential components : turning the hips, pivoting the supporting foot, swinging the arms, and striking with the lower shin or instep (Young, 1991). The roundhouse kick generates a lot of force levels to the three primary targets of the roundhouse kick which are the thighs, trunk (chest and ribs), and head. In order to obtain more force at impact, the movement of four essential components are needed to be considered. In addition, the linear and angular velocities of the kicking leg are also important in order to obtain high force at impact of Thai Boxing roundhouse kicks.

Although the roundhouse kick is a very powerful weapon, protective gear is not required to be worn in Thai Boxing. Consequently many Thai boxers have received brain concussions, fractured bones and soft tissue injuries as a result of being hit by roundhouse kicks. Up to this time there has been no scientific research concerning any Thai Boxing maneuver. The purpose of this study is to do a scientific analysis of both kinetic and kinematic parameters of the roundhouse kick in Thai Boxing. The results of this study will provide Thai Boxing promoters, coaches, and boxers with a better understanding of the mechanics of the body in performing the roundhouse kick. This information could be used for training purposes as well as for the evaluation of new rules that may be helpful for the preventing of injuries. Such rules could include the requiring of protective gear or the limiting of legal striking areas.

The purpose of this study was to analyze the Thai Boxing roundhouse kick. In order to accomplish the primary purpose of this study, a kicking bag was designed and constructed. The study also required the development of a force measurement system that could be used with the kicking bag. This measurement system was based on a triaxial accelerometer inserted into the center of the bag. Experienced Thai Boxing performers from the local area were the subjects used in the study.

1.1 Statement of the Purpose

The primary purpose of this study was to determine force, and velocity characteristics of Thai Boxing roundhouse kicks. Specifically, the study sought to determine all kinetic and kinematic variables at three separate kicking height levels. The kinetic variables included peak force, and impulse. The kinematic variables included final linear velocity of the kicking ankle, linear velocity of the kicking ankle and knee, angular velocity of the knee, and the angular velocity of the shank and the thigh projected onto the horizontal plane. Another concern of the study was to determine if there was any relationship between leg strength and the kinetic variables.

The study also sought to measure the relationships between final linear velocity and the kinetic variables.

1.2 Research Hypotheses

Based on review of the literature as well as on practical experience, the following research hypotheses were proposed. For the force variables, linear velocity variable and the height level of kicks, it was hypothesized that lower level of kicks would generate higher values for peak force and impulse, and final linear velocity of the kicking ankle at impact than the higher level of kicks. For the relationship between leg strength and force variables, it was hypothesized that peak force and impulse would increase with peak torque of the leg strength. For the relationship between force variables and linear velocity of the kicking leg, it was hypothesized that peak force and impulse would increase with final linear velocity of the kicking ankle.

1.3 Delimitations of the Study

The following delimitations are considered :

1. The study conducted in the Biomechanics Laboratory at Oregon State University, Corvallis, Oregon.
2. This study is delimited to the roundhouse kick with three different target height levels.
3. This study used only right-footed boxers.

1.4 Limitations of the Study

This study was limited with respect to :

1. the relatively small sample size.
2. the use of a kicking bag as the target with compliance somewhat different than the human body.

3. the use of an accelerometer to detect the acceleration of the kicking bag in order to calculate force, as the accelerometer inside the bag will not respond exactly proportional to the force applied to the surface of the bag.
4. the small number of trials because of the limited ability of the foot to tolerate injury.
5. limited to recreational ability subjects. Elite performers might be expected to move with greater speed and apply greater force.

1.5 Assumptions of the Study

In this study, the following assumptions are made :

1. Subjects performed to the best of their abilities at the time of testing.
2. Kicking a bag required similar kicking mechanics to those found in a real Thai boxing match.
3. Peak acceleration of the kicking bag was directly proportion to the force applied to the bag.

1.6 Definition of Terms

Final velocity : the velocity of the ankle at time of contact with the kicking bag.

Impulse : the area under a force-time curve which equals the change of momentum of a body due to action of the force on the body. In this study, the area was determined by numerical integration of force over time which started from the point of contact to the second minimum force (see Figure 1).

Length of kicking leg : the distance from the greater trochanter of the femur to the lateral malleolus.

Peak force : the apex of the impact curve indicating the highest level of force generated within that curve.

Roundhouse kick (right-footed) : a kick started by turning the hips followed by the pivoting of the supporting foot and accelerating the lower leg or instep of the kicking leg from right to left into the target.

Thai Boxing : a style of boxing that originated in Thailand and which allows the use of fists, elbows, knees, and feet for striking the opponent (see Figure 2).

Three different height levels of kicking : low, middle, and high levels of targets at the middle of the kicking bag which corresponded to 50, 100, and 150 percent respectively of the leg length of each subject.

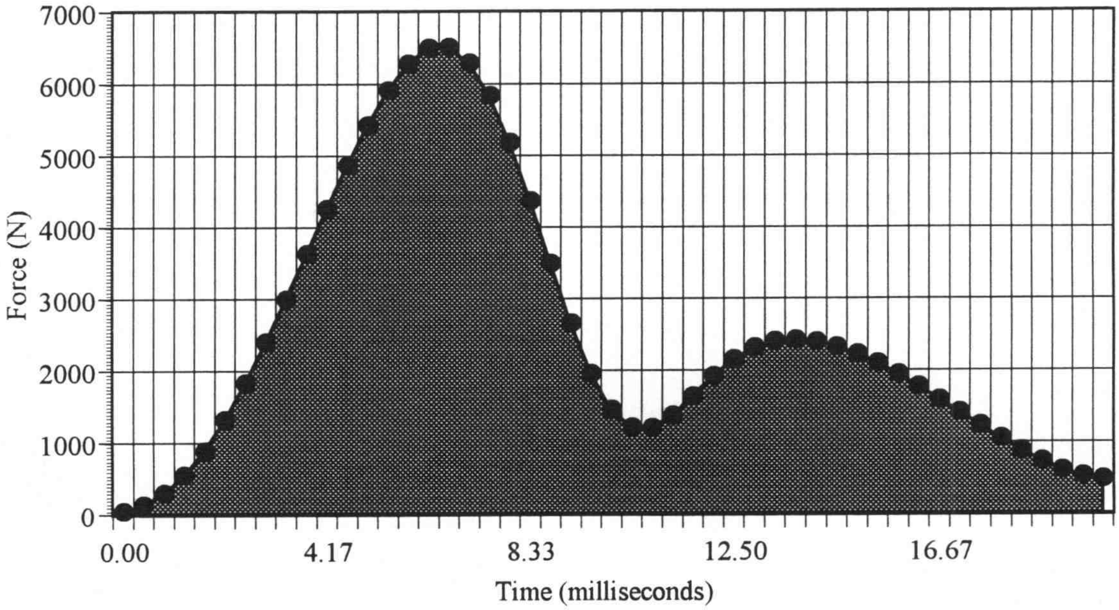

Figure 1. Impulse of typical kick was determined by numerical integration to find the area under the curve.

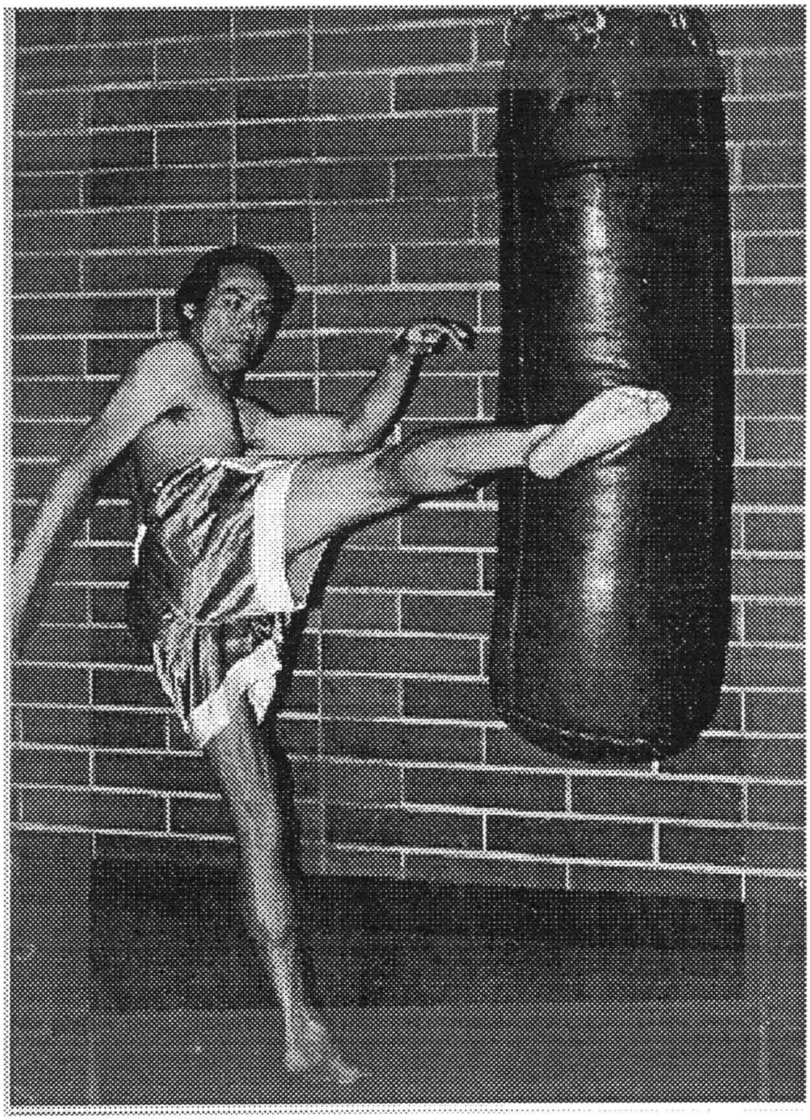

Figure 2. Thai Boxing roundhouse kick

Chapter 2
Review of Literature

This chapter contains a review of : (a) the history of Thai Boxing, (b) Thai Boxing kicks, (c) general kicking studies, (d) other martial arts kicking studies, (e) force studies, (f) general force and impact force studies, (g) accelerometer studies, and (h) motion analysis.

2.1 History of Thai Boxing

Thai Boxing has been a traditional martial art and sport for Thai people since they moved from the Southern part of China into the areas around the Maekong and Salaween rivers on South East Asia, and is still the most popular professional sport in Thailand today (Mitchell, 1989). There is little written record of the early history of Thai Boxing. The first written documents concerning Thai Boxing history became available during the Ayudhaya era in Thai history. This important period of Thai Boxing history was from 1767 of Ayudhaya era (Kraitus, 1988), when the city was invaded and destroyed by Burmese who took many Thai people as prisoners. At that time, King Mangra of Burma decided to have a celebration for seven days and seven nights in honor of the Chawadagong Pagoda in Hong Sawadee in Burma. He ordered a royal presentation of Thai Boxing matches between Thai and Burmese fighters. Nai Khanom Tom, a famous fighter from Ayudhaya, represented Thai Boxers. He used legs, knees, elbows, and fists to beat ten of his Burmese opponents. As a result, King Mangra gave him a reward and he became famous throughout both Burma and Thailand. Thus, Nai Khanom Tom is considered the first Thai boxer to have bestowed honor to the art of Thai Boxing. Thai people also respectfully refer to him as the father of Thai Boxing (Kraitus, 1988). During the Rattanakosin (Bangkok) period, Thai Boxing became a popular sport through the country of Thailand. Especially in the 19th century, the Kings of Thailand were interested in and supported Thai Boxing tournaments. At this time Thai Boxing became the most representative sport of Thai culture (Kraitus, 1988).

Today, Thai Boxing is known all over the world as a martial art and as a competitive sport. Typically, Thai Boxing consists of two essential parts : the first part, which is called Wai Khruu, is a dance-like movement reflecting the feeling of gratitude in the mind of every Thai boxer as he pays homage to his father, mother, and teachers for the love and care he has received. The second part is the fighting part which makes use of eight weapons which are : both fists, elbows, knees, and feet.

2.2 Thai Boxing Kicks

There are various types of Thai Boxing kicks. Technically, they are classified by the height level of the kick and are classified as basic, medium, and high level kicks. At every kicking level the roundhouse kick is considered to be the most effective. It can be broken into four essential components : turning the hips, pivoting of the supporting foot, swinging the arms, and striking with the lower leg or instep (Young, 1991).

The first component of the roundhouse kick is the turning of the hips. The rear foot is used for the most powerful roundhouse kick. The boxer raises the heel of the rear foot off the ground as he begins to rotate the hips. This position facilitates a full and rapid movement of the hips. Then as the toe leaves the ground the front foot pivots. This foot pivoting of the supporting leg occurs while the rear foot is swung counterclockwise past the front foot until it almost points at the target. At this point, the body weight must be centered on the ball of the supporting foot.

The next component is swinging of the arms. In order to produce the greatest possible force from the kick, there must be some movement that balances the angular momentum produced as one rotates the leg. That movement is the swinging of the arms. For instance, if one supposes a stance with the left foot forward, when the roundhouse kick is started by lifting the backward right heel, the right hand begins a downward motion in opposition to the right leg as the left hand and arm move across the body from left to right. At the same time, the left hand and arm move up slightly to about jaw level to protect against counterattack. The last component of the roundhouse kick, which is unique to Thai Boxing, is using the lower end of the tibia or instep for striking at the calves, thighs, floating ribs, arms, and head of the opponent (Mitchell, 1989, Young, 1991).

2.3 Literature on General Kicking

Most kicking studies have been focused on the efficient execution of the skill of ball kicking. The basic concern about the kicking motion in these studies is the sequence of segmental rotations in a kick. The kicking motion is started from the pelvis rotation followed by hip flexion which brings forward motion of the thigh, and the knee extension comes in near the end to add to the final speed to the kicking foot. (Robert & Metcalfe, 1968; Hays, 1985; Kreighbuam & Barthels, 1985). In addition, a correct sequential timing of body segment movement is an essential factor for the kicking of a ball (Dunn & Putnam, 1988).

In segmental motion analysis, the momentum contribution of the upper segment to the lower segment is an interesting question for ball kicking. In the kicking motion the lower extremity of the body consisting of two rigid segments, the thigh and the lower leg, plays a major role in segmental motion. Putnam (1981, 1983) determined the effect of the motion of one segment on the adjacent segment motion in terms of the sequential time of the segmental motion of a punt kick. There was positive relationship between angular velocity of the thigh and angular velocity of the shank from the beginning of kicking motion until before the knee angle reached 90°. After the knee angle reached 90° called the latter half of kicking motion, the angular velocity of the thigh started to decrease while the angular velocity of the shank continuously increased to reach the maximum velocity as the foot contacted the ball. Putnam concluded that in the latter half of the kicking motion, the decrease in angular velocity of the thigh did not influence the angular velocity of the shank. Dunn and Putnam (1988) investigated the influence of the lower leg motion on the deceleration of the thigh in three different speeds of kicking. When the thigh was decelerating, the resultant joint moment acting on the hip remained positive throughout the kick. During this motion, the angular velocity, and angular acceleration of the shank were negative which caused the deceleration of the thigh. These results were similar to the finding of Putnam (1983) which found that the thigh deceleration in a kicking motion was influenced by the motion of the shank rather than the resultant joint moment acting on the hip.

Tant (1990) investigated the timing, sequence, and segmental interactions of three different soccer instep kicks. Eight male Division I intercollegiate soccer players were filmed from two views with 16 mm high speed cameras at 200 frames/sec. She found that there was no significant difference between kinematic variables (angular velocity, and relative timing) of the pelvis, thigh, and lower leg during three different styles of soccer instep kick. Furthermore, she also found that in all three kicks there was a simultaneous movement pattern between pelvis and thigh whereas a sequential pattern of segmental movement in all three kicks occurred between thigh and lower leg.

2.4 Literature on Martial Art Kicks

The research on martial arts kicking has focused on Karate and Taekwondo. In Karate kick studies, Jordan (1973) investigated six selected karate arm and leg techniques included the side kick, back kick, front thrust kick, straight punch, reverse punch, and vertical punch. Two 16 millimeter Locam high-speed movie cameras operating at 200 frames per second and four strain gauges attached to a steel plate mounted on a steel base were utilized for his study. A mean maximum force of the side kick, front thrust kick, and back kick were 717, 710, and 687 pounds of force respectively. A mean maximum force of the reverse punch, vertical punch, and straight punch were 352, 347, and 322 pounds of force respectively. Moreover, Jordan found that maximum force of leg and arm techniques increased as height, body weight, arm length, and leg length variables increased. Powell (1989) analyzed three styles of the karate back punch and side kick utilizing a Bolex high speed camera at 64 frames per second and a force plate attached to a heavy bag weighing 31.5 kilograms. The mean force of the traditional, modified, and western style of back punch were 239.4, 244.5, and 296.5 kilograms force respectively with mean final velocity of 4.29, 5.89, and 7.08 m/s respectively. The mean force for three types of side kicks, the snap, modified, and thrust kick were 334.5, 389.9, and 604.5 kilograms force respectively with the final velocity of 3.81, 4.34, and 4.77 m/s.

In studies of Taekwondo kicks, Park (1989) investigated selected kinematic and kinetic parameters of the three types of Taekwondo front kicks, kicking with the trunk forward (KF), kicking with the trunk straight (KS), and kicking with the trunk backward (KB). An AMTI force platform and 16mm camera at 100 frames per second were employed to determine ground reaction force of supporting foot and kinematic parameters. During the front kicks, the attack time of KB style (330.0 msec) was faster than that of the other two front kicks style, KS (350.0 msec), and KF (353.8 msec). The mean resultant foot velocity at impact of the KF style was 7.49 m/sec which was greater than the KS (7.10 m/sec), and KB style (6.89 m/sec). The maximum muscle moments of segment joints occurred as the direction of rotation reversed from flexion to extension of joint. A mean maximum vertical ground reaction force on the supporting foot (966 N) occurred approximately at the time hip flexion started.

2.5 Literature on General Force and Impact Force Studies

In biomechanical analysis of human motion it is necessary to obtain quantitative measures of the force related to the activity of each study. Typically, several types of force measuring devices and accelerometers are available to measure force in studies of human movement. However, force measuring devices are more widely used than accelerometers in the area of biomechanical study.

Knudson and White (1989) measured the force on the hand in the tennis forehand drive. Force sensing resistors were utilized to measure the force on the hand of seven skilled tennis players. The magnitude of the peak post-impact force on the hand had considerably higher variability (ranging from 4 to 309 N) than that of pre-impact force (ranging from 5 to 57 N). Knudson (1991) continued to examine the force on the tennis one-handed backhand utilizing two miniature load cells mounted on a mid-sized racket. The mean force on the thenar eminences of the hand in preparation for impact for advanced players (40.3 N) was significantly greater than that of the intermediate group (21.4 N). The mean post-impact peak forces on both the thenar (48.3, 33.0 N) and hypothenar (50.7, 43.1 N) of both groups were greater than the force in preparation for impact.

Miller, Pate, & Burgess (1988) examined the relationship between foot impact force and the magnitudes of the changes in markers of intravascular hemolysis during running uphill (+6%) or downhill (-6%) on a treadmill at 215 m/min for 10,000 foot-strikes. Blood samples were collected immediately before exercise, and immediately, 1 hr, and 2 hr. after the exercise in order to determine hemoglobin concentration (Hb), Hematocrit (Hct), plasma free hemoglobin (PFHb), and haptoglobin concentrations (Hp). Foot sole force transducers were employed to measure foot impact force. They found that mean foot impact forces were 171.4 kg force in the uphill run and 190.5 kg in the downhill run. However, there was not statistically significant difference in foot impact force between the downhill and the uphill running due to the great variability in foot impact forces among the subjects. Hp was significantly decreased while PFHb was significantly increased after treadmill running in both conditions.

Frederick, Hagy, & Mann (1986) examined the vertical impact force during running utilizing a Kistler force platform and cinematography. Subjects ran at three different speeds (3.4, 3.8, and 4.5 m/sec) and were filmed at rate of 50 frames per second. Increases in impact force during running were associated with an increase in speed and body weight. They found that the variables most significantly associated with vertical impact force were weight, running speed, vertical excursion of the hip, foot dorsi-flexion angle, half stride length, and step length. The impact force of three running speeds were 203.4%, 232.9%, and 286.3% of body weight respectively.

Nigg, Herzog, & Read (1988) investigated the effect of viscoelastic shoe insoles on vertical impact forces in heel-toe running. The subjects wore two types of shoes (G1,G2) with five different insoles (one regular, two viscoelastic, and two elastomer-viscoelastics insoles) and ran over a force platform with a constant speed of 4 m/s. Two high speed camera at 100 frames per second were utilized to film each subject from both the lateral and posterior views. The impact forces variables(vertical peak force, time to peak, and maximum vertical loading rate) of four tested viscoelastics insoles did not differ from regular insoles furnished in running shoes. In addition, the viscoelastic did not affect kinematic variables of the lower extremities in a systematic way.

2.6 Literature on Accelerometer Studies

In general, there are a few tools which have been frequently utilized in the area of biomechanical research. These include goniometers, electromyograms, cameras, and force measuring devices. The accelerometer is another apparatus often employed in gait study. In order to derive acceleration data from human movement, technically, there are two configurations of accelerometers typically utilized in walking and running studies. These are the skin-mounted type and the bone-mounted type. Several studies have utilized skin-mounted accelerometers.

Hamill et al. (1984) utilized a high speed camera and a lightweight accelerometer to determine the effects of grade running on kinematics and impact accelerations of 6 different grades and with running at 3.8 m/sec on a treadmill. There were significant decreases in leg shock with increasing grade. Kinematic variables, Maximum Knee Flex Velocity (MKFV), Knee Angle, and Ankle Angle were changed over the grades. Increasing knee flexion velocity occurred as grade decreased. They concluded that the involvement of the knee and ankle joints attenuated the impact force during running.

Gross & Nelson (1988) investigated the shock attenuation role of the ankle during landing from a vertical jump. Two piezoelectric accelerometers mounted at the medial calcaneus and distal antero-medial tibia, a force platform and high speed cinematography were utilized to collect the data. Eleven male recreational basketball players performed two landing styles (metatarsal and heel contacts) on three surfaces (aluminum, tartan, and foam) for vertical jumps. They found that there were no significant differences between peak acceleration at calcaneus and tibia across landing surfaces and landing styles. Peak vertical force of two landing styles did not vary across landing surface. However, the magnitude of vertical forces of heel contact landing style was approximately 2.2 times more than that of the metatarsal contact. The ankle joint motion varied a little across surfaces but did not vary across landing styles. They explained that the range of cushioning used in their study was insufficient to significantly change the process of the biological shock attenuation during vertical landing. Furthermore, they explained that the role of the ankle in damping impact during vertical landing was individually controlled by ingrained kinematic patterns as well as structural damping components such as tissue, cartilage, and bone.

Bone-mounted accelerometers provide more accurate measure than that of the external attachment (Henning & Lafortune, 1988). A few studies have been done utilizing internal attachment (Ziegert & Lewis, 1979., Lafortune, 1991). Ziegert & Lewis (1979) examined the effect of soft tissue on measurements of vibrational bone motion by skin-mounted accelerometers using two types accelerometers, 1.5-g and 3.4-g. An accelerometer was held against the skin with elastic strap to measure skin surface acceleration. Bone acceleration was measured by mounting an accelerometer on a needle and inserting the needle through the soft tissue. In order to verify the accuracy of the needle mounted accelerometer on bone acceleration measure, an identical accelerometer was glued on the surface of the bone which was as close to the needle as possible. They found that the needle-mounted accelerometer provided accurate result for measurement of bone acceleration as compared to an accelerometer cemented directly to bone. The small mass accelerometer (1.5-g) response was more accurate to measure bone acceleration than a larger mass accelerometer (3.4-g) in both techniques, needle-mounted and skin-mounted.

Lafortune (1991) investigated three-dimensional acceleration of the tibia during walking and running utilizing a 6-g bone-mounted triaxial accelerometer on the tibia. The mean magnitude of peak resultant acceleration transients (PRE) during foot-ground contact in walking in barefoot and shod condition were 3.74 and 2.70 g respectively while the PRE of the slower running speed (3.5m/sec) and the faster running speed (4.7m/sec) were 7.54 and 10.64 g respectively. In walking, the pattern of tibia acceleration in the AP direction of both conditions were similar, the peak negative antero-posterior (PNAP) acceleration occurred at the beginning immediately followed by PPAP. On the other hand, in running, PPAP occurred at the beginning and immediately followed by PNAP. The mean maximum medio-lateral (ML) acceleration of the tibia of barefoot and shod conditions in walking were 1.28 and 0.90 g respectively while the mean ML acceleration for both running speeds showed large negative peaks (PML) shortly after foot strike which were 4.68 and 5.01 g respectively for the slower and faster running speeds.

However, there are some factors concerning measurement error that researchers have to be aware of when utilizing accelerometers to measure impact in human movement. The mass of the accelerometer is a cause of measurement error. Henning & Lafortune (1988) reported that there was a 50% error occurring when utilizing a skin-mounted accelerometer package with a mass that exceeded 6 grams. In addition, the attachment of the accelerometer is another factor which needs to be considered. Henning & Lafortune (1988) suggested that utilizing the internal attachment accelerometer provided more accurate measures than that of the external attachment.

Typically, the use of accelerometers is the more direct approach to measurement of the acceleration of the segments of body, it also has been utilized to indirectly measure the reaction forces associated with a given acceleration. When the known mass is moving with a given acceleration, the force can be derived using the Newton's second law of motion, $F = ma$.

Franks, Sanderson, & Donkelaar (1990) compared acceleration-times histories recorded during a simple arm flexion/extension movement at a fast pace (average angular velocity = 375°/sec) or at a slow pace (average angular velocity = 100°/sec) for two complete cycles. Directly measured accelerations from Bruel piezoelectric uniaxial accelerometer model 4332-35 were used to obtain an optimal filter cut-off frequency for displacement data. The number of significant deviations, the derived and directly measured acceleration-time histories were equal when angular displacement was filtered at upper cut-off frequency of 10 Hz. The derived acceleration-time histories of fast movements were relatively smoother than that of the slow movements across the entire range of 5-30 Hz cut-off frequencies. They recommend that the cut-off frequency of the slow movement would be 18 Hz, while in the fast movement condition this value would be 37 Hz.

2.7 Motion Analysis

As the demand for more detailed information in the area of human movement analysis has increased, the technique of cinematography has become one of the major research tools in sport science. In collecting kinematic data, this technique can provide accurate descriptive information.

The equipment which has been most widely utilized for cinematographical method includes movie cameras, still cameras, and video cameras. High speed 16-mm movie cameras have been frequently used in the research of human movement over the last three decades. However, the use of a 16-mm movie camera has some limitation in terms of the amount of time required to obtain and analyze the data from the film. Recently, the use of high speed video cameras and high speed digital computers for data processing has made it possible to collect and analyze the same data in a much shorter period of time. However, in order to properly study human motion utilizing cinematography, the researcher should still have a general understanding of cameras, lenses, methods of film calibration, fundamental of filming, and film analysis techniques (Miller & Nelson, 1973).

When cinematography is utilized to derive kinematic data, the use of a 2-D multiplier and 3-D analysis technique have played a major role as the essential tools of human movement study. The use of 2-D analysis is a simple method of providing data to analyze locomotion. Its requires one camera perpendicular to the plane of the motion. However, 2-D analysis technique is limited in analyzing complicated human movement. Thus, the use of 3-D methods is becoming an appropriate technique providing more accurate data as compare to 2-D analysis in complex motion.

A 3-D analysis technique which has been used extensively in the analysis of human movement is the Direct Linear Transformation (DLT). This method was developed by Abdel-Aziz and Karara at the University of Illinois (1971). Since then, several assessments have attempted to overcome the shortcoming and source of errors of using the DLT method.

The DLT method attempts to predict object space coordinates from image coordinates. It requires at least two cameras and six or more known control points to be used to determine 11 DLT parameters or camera constant parameters which are arranged in two independent linear equations. After 11 DLT parameters are known, the object space coordinates are predicted from the film measurement. However, the DLT method has some major shortcomings when used to analyze events which take place over large volumes (Timothy, Koh, & Hay, 1993) including the errors associated with camera position, lens distortion, control point configuration, image size, digitizing accuracy, and extrapolation (Challis & Kerwin, 1992, Wood & Marshall, 1986). Several assessments have been developed in order to overcome some of the these disadvantages(Challis & Kerwin, 1992, Ball & Pierrynowski, 1988, Dapena, Harman, & Miller, 1982, Haan & Brinker, 1988, Shapiro, 1978, Timothy, Koh, & Hay, 1993, Walton, 1979, 1981, and Wood & Marshall, 1986).

Shapiro (1978) evaluated the DLT method utilizing high speed cinematography with three tests (two static and one dynamic). The first test involved filming 48 stationary points; 20 points were selected to predict the DLT parameters, and the rest were treated as unknown points. The average errors associated with x, y, z coordinates for 28 unknown points were 0.43cm (x), 0.51 cm (y), and 0.44 cm (z).

A second test used a meter stick placed at the edges of the camera field to test coordinates outside of the control object space. The calculated length of the meter stick was found to vary by 2% to 4% from the known length. The last test, dynamic test, involved filming a golf ball falling in free fight. The acceleration of the ball ranged from $-9.5\ m/s^2$ to $-10.0 m/s^2$. These calculated vertical accelerations were 1% to 4% of the value of the gravitational acceleration ($-9.8 m/s^2$).

Walton (1979, 1981b) provided extensive documentation of the theory and application of the DLT method for using high speed cinematography. The method of camera setting up and filming of control objects was similar to Shapiro (1978). However, Walton provided additional information about cameras, lenses, control points, film, and temporal measurements. In order to obtain good results, there were many factors need to be considered such as the lens factors including focal length, maximum relative aperture, and maximum relative distortion. Moreover, the precision location and uniform distribution of the control point were important. With reference to camera image, three vectors (n_x, n_y, n_z) and original point (A), defined a three-dimensional reference frame fixed in the object space. All the points within the volume of object space assume to have three-dimensional object coordinates (object-reference-frame). N_u and N_v are non-unit vector and parallel to the plane of image which defined a two-dimensional coordinates (image-reference-frame). The two linear equations required for object-to-image transformation were (Walton,1979):

$$U = \frac{Ax + By + Cz + D}{Ex + Fy + Gz + 1}$$

$$V = \frac{Hx + Jy + Kz + L}{Ex + Fy + Gz + 1}$$

The specific values must be provided for the calibration coefficients of A through L from transformation matrices. Three-dimensional object-coordinates need to be determined with using two cameras. Specific prediction for X, Y, and Z can be obtained using a linear least squares approximation. The generalized three-dimensional model was tested and validated. A first test involved filming 18 golf balls suspended from horizontal surface. The 8 points at the corner of the outer cube used as control points to predict the location of the other 10 points. The difference between the known location and the computed location was sufficiently small to be within the bounds of measurement error involving in locating the ball. A second test was to investigate the object-point outside of the control points. The mean deviations from the known locations were small. A third test was dynamic test involved filming a lobbed golf ball. The estimation for acceleration due to gravity was between 9.778 to 9.895. The final test involved performing of human subject in trampoline maneuver. The performer was filmed by four cameras located uniformly around the trampoline. The errors associated with precisely locating body landmarks were introduced. The generalized three-dimensional model was found to be an accurate model for determining the spatial object points (Walton, 1979).

Dapena, Harman, & Miller (1982) developed a three-dimensional motion technique with a relatively simple filming procedure and a greater ability to reconstruct coordinates in larger volumes than the DLT method. The unknown values of the Non-direct linear transformation method included 1) coordinates of the projected images (measured from film), 2) internal camera parameters (computed from measurements of a projected image of a cross), and 3) external camera parameters (computed from a series of point of the unknown object space locations). In order to solve a system of three unknowns, the use of four linear equations is necessary. The validation procedure utilized ten poles marked with five targets were placed within a volume of about 5m x 5m x 2m to form the control object. A 24-target grid was inserted within the volume defined by the pole targets. The coordinates of grid targets were surveyed, the locations of the poles were not surveyed. For a 15-point control object, the root mean square errors averaged 15 mm, 13 mm, and 6 mm, and the errors in relative length were 0.5% (X), 0.7% (Y), and 0.5% (Z). The use of this technique would reduce the number of objects to be transported and permit a control object in a large area to be analyzed. The accuracy of the method was found to be consistent with other methods presented as the root mean squares.

MacReflex motion analysis system is relatively new instrumentation which is available to obtain coordinate data on human motion. The system utilizes two or more cameras and six or more control points for calibration like other three-dimensional analysis techniques. This system utilizes image sensors and processors with real-time tracking procedures in order to detect markers with high reliability. The MacReflex system utilizes a nine control point structure of dimensions 1 x 0.5 x 0.45 m for calibration which is a relatively small structure. There are relatively large 3-D coordinate prediction errors for points outside the bounds of the control point structure (Levy & Smith, 1995). However, the use of the MacReflex system to predict 3-D coordinates object space within the control point structure is reasonably accurate (Levy & Smith, 1995).

2.8 Summary

The motion of body segments in general kicking and ball kicking has been studied in detail by numerous researchers. A few research studies have been devoted to the study of kicking in the martial arts, particularly, Karate, and Taekwondo. There has not been any previous research studying the motion of Thai Boxing kicks. Most research studies of kicking have primarily focused on utilizing cinematographical techniques to provide a description of kicking styles. There is a limited amount of research dealing with impact force measurement in various martial arts. Typically, a force platform has been utilized to measure impact force during walking and running. However, in order to measure impulse or impact force for specific movements, such as in martial arts, the force measuring devices have to be modified. The specific modifications required will be unique for each study. In the case of Thai Boxing kicks, it is not realistic for the subjects to kick a fixed or rigid force plate. The kicking of a human opponent is simulated more closely by using a kicking bag as a target. Since this bag is not fixed, i.e., it is free to swing, accelerometers inside the bag were used to indirectly obtain force measurements. Although no previous studies have used accelerometers to measure force, the reliability and validity of accelerometers have been previously established and widely accepted in the area of mechanical engineering and human movement study.

Presently, the analysis of human movement requires obtaining meaningful information from a combination of cinematographical and force measuring techniques. The present study will provide a scientific analysis of the roundhouse kick in Thai Boxing by combining an accelerometer based assessment of impact data with a 3-D analysis of kinematic variables.

Chapter 3
Methods

Muay Thai, or Thai Boxing, is a unique martial art and a method of self-defense. It started in Thailand in ancient times as a means of self-protection, but today it has become one of the most popular individual sport programs in the world. Thai Boxing rules are quite different from international boxing rules. A Thai Boxing match has five rounds of fighting with three minutes per round and two minutes rest between rounds. Thai Boxing allows the use of four offensive maneuvers : punches, elbow-strikes, knee-strikes, and a variety of kicks to attack any part of the opponent's body. Among the four attacking skills of Thai Boxing, the roundhouse kick is the most dangerous weapon with which to devastate the opponent (Young, 1991).

Although the roundhouse kick is a powerful weapon, protective gear is not required to be worn in Thai Boxing. Consequently many Thai boxers have received brain concussions, fractured bones and soft tissue injuries as a result of being hit by roundhouse kicks. Despite the frequency of these serious injuries, there has been no scientific research concerning any Thai Boxing maneuver.

The purpose of this study was to determine a kinetic and kinematic analyses of three height levels of the roundhouse kick in Thai Boxing. While the kinematic variables were measured using conventional motion analysis procedures, the kicking forces were estimated using acceleration data rather than direct force measurement.

3.1 Instruments

In order to obtain the kinetic and kinematic characteristics of Thai Boxing roundhouse kicks the use of the following instruments was necessary.

3.1.1. Kicking Bag and Accelerometers

In biomechanics research, reaction forces are usually measured by force plates mounted on an immovable surface. However, in this study it would not be possible for the subjects to exert their maximum force in kicking that type of solid surface because of the potential for injury. In addition, the kinematics would likely be different with respect to kicking an immovable surface as compared to kicking a human body. For these reasons, a kicking bag with a triaxial accelerometer inside was designed to be the kicking target.

The kicking bag was used to measure the acceleration which could be converted to a measure of the force of the Thai Boxing roundhouse kick striking the human body. Three PCB uniaxial accelerometers were orthogonally mounted together on a 1-centimeter steel cube to form a triaxial accelerometer. The specifications for each of these accelerometers are in Table 1. This triaxial device was implanted at the center of a bowling ball. A hole was drilled into the center of the bowling ball where the steel cube was secured by modeling clay. The mass of the bowling ball was 6.4 kilograms and the diameter was 22.3 centimeters. The bowling ball was wrapped with condensed foam rubber and then placed inside a leather kicking bag. Sand and additional condensed foam padding was also placed inside the kicking bag surrounding the bowling ball. The leather kicking bag was about 50 centimeters in diameter, and had a mass of 40 kilograms (see Figure 3). These characteristics provided the following desired conditions: a) The sand and condensed foam padding surrounding the bowling ball made subjects feel confident of foot safety during their kicking trials; b) the kicking bag was allowed to swing freely like a pendulum. The swinging angle for a typical kick was between 10° to 25°; c) the weight of the bag (compared to a heavier or a lighter bag) resulted in sufficient acceleration to be reasonably measured above noise levels while having sufficiently large inertia to simulate the response of a human body. As shown in Figure 4 the kicking motion occurred directly in the x direction. That is, the acceleration signals obtained in this direction (x-horizontal) were typically 20-50 times larger than on the other directions (see Figure 5).

Table 1

Accelerometer specifications

Axis	X	Y	Z
Model	303A02	303A02	303A02
S/N	11333	24642	22164
Frequency Range (Hz)	1 to 10,000	1 to 10,000	1 to 10,000
Amplitude Range (±g pk)	500	500	500
Sensitivity (mV/g)	10.24	10.60	11.71
Input TC (sec)	≥0.5	≥0.5	≥0.5
Natural Frequency (kHz)	≥100	≥100	≥100

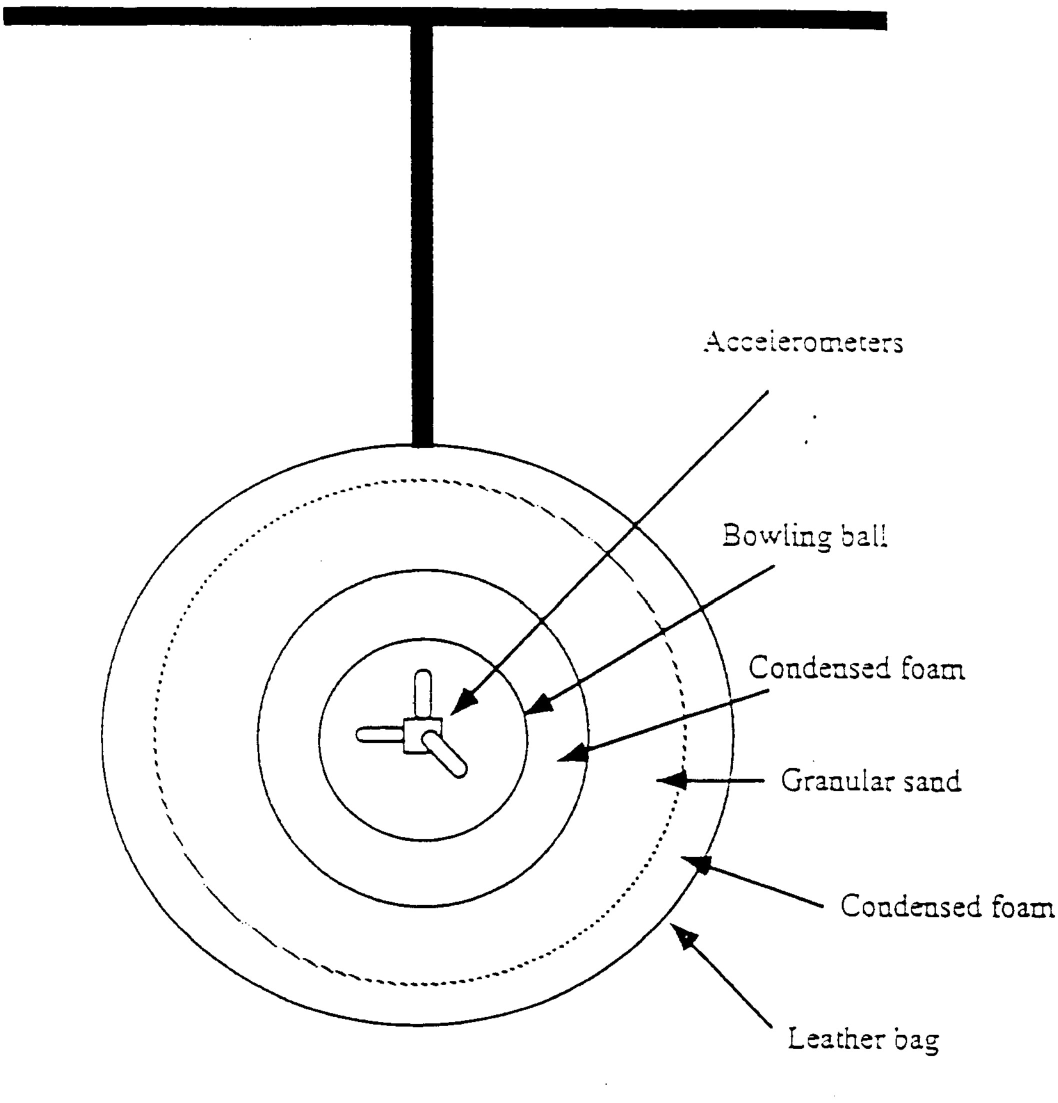

Figure 3. The dimension and components of the kicking bag

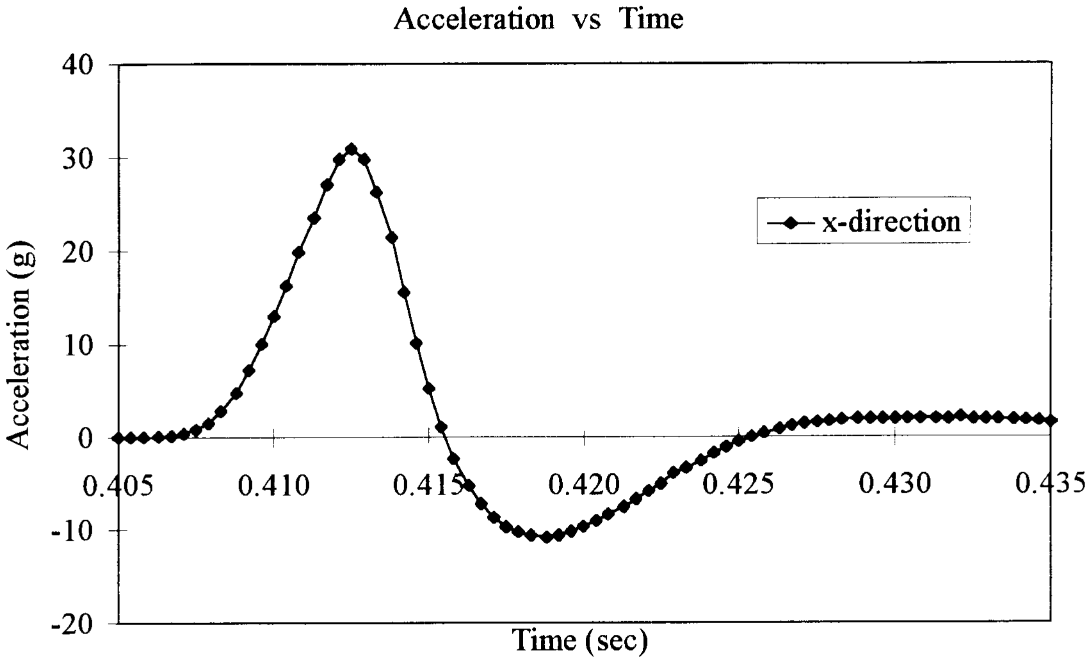

Figure 4. Acceleration curve in x direction.

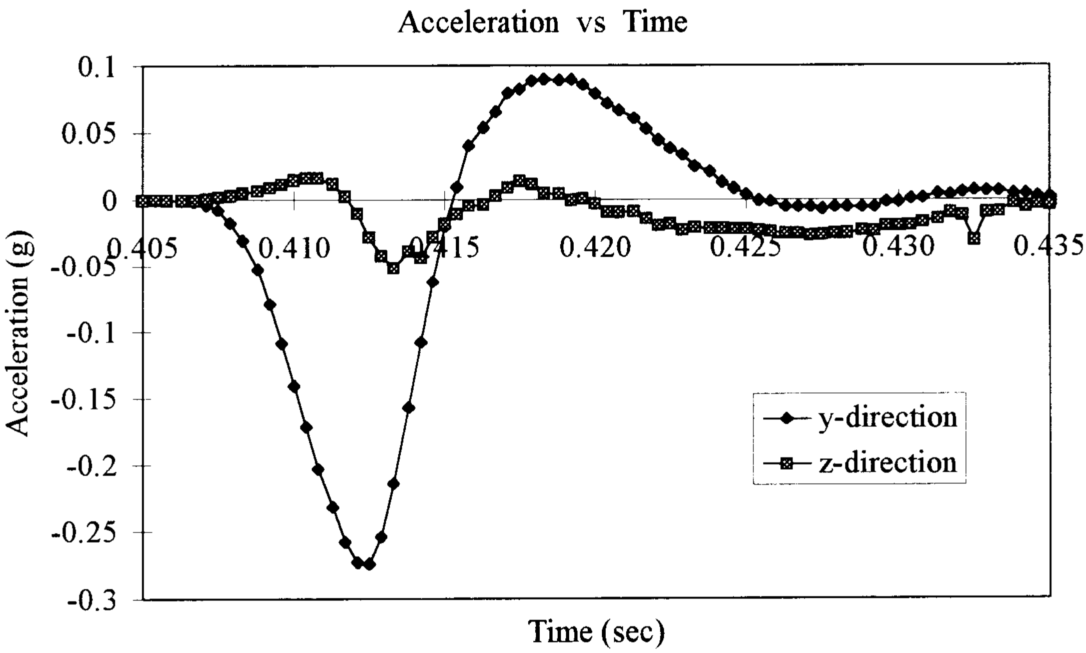

Figure 5. Acceleration curves in y direction and z direction.

3.1.2 Signal Conditioner, Terminal Accessory Board, and PC Computer with A-D Board

Acceleration signals from the accelerometers were sent to an ICP battery-powered signal conditioner model 482A16. This amplifier was utilized for signal conditioning with a gain of 10. The amplified signals were sent to a terminal accessory board and to a PC computer with a Metrabyte A-D board Dash-16. The A-D board was set at ± 5 volts of input range in bipolar mode.

3.1.3 Computer Programs

One computer program was written to collect the acceleration data. After the three dimensional acceleration data were recorded another program was used to handle the filtering and calculations of force from acceleration data. Each program was written in Microsoft Quick Basic. The first program collected data from the triaxial accelerometer in digital units at a sampling frequency of 2400 Hz with 1 second of time duration for each trial. A second program was utilized to convert the acceleration from digital units to a data file, and to derive the resultant acceleration ($R = \sqrt{(x^2+y^2+z^2)}$) from the triaxial accelerometer. According to Newton's second law, $F = ma$, the acceleration data were used to calculate force. The force data were smoothed using the Butterworth digital filter technique with a cutoff frequency (f_c) of 280 Hz determined by utilizing the residual analysis method. This method calculates the sum of the differences between raw and filtered data for each f_c. The residual of each f_c is plotted. If there is no signal in the data, the residual plot would be a straight line, but if the data contain both signal and noise, the residual plot line will depart from the straight line. Noise and signal distortion are the two important factors to determine f_c. More noise is allowed to pass as f_c is increased while signal distortion occurs as f_c is reduced. To obtain a balance between the degree of noise allowed to pass and the degree of signal distortion, Winter (1990) suggested extending the straight line of the residual plot until it intercepts the residual axis. From this intercept a straight line should be drawn parallel to the f_c axis. The point where this line crosses the residual plot line is the compromise point between the amount of signal distortion and the amount of noise. After filtering the force date the program identified the peak force. Finally, the impulse was computed using the integrated data technique based on the trapezoid rule, i.e., the area of the trapezoid formed is equal to the average of the two data values multiplied by their separation:

$$I = \sum_{i=1}^{n-1} (Y_i + Y_{i+1})(X_{i+1} - X_i) / 2$$

[I = impulse value; Y = force data value; and X = time data value (Orvis, 1993).]

3.1.4 MacReflex Motion Analysis System

To obtain 3-D coordinates of the roundhouse kicks, a MacReflex motion analysis system was utilized. This system had 3 cameras operating at 120 Hz and filmed an area with a total volume of 1.5 m x 2.0 m x 1.7 m. as delineated using five survey poles that were utilized for 3-D calibration. This 3-D calibration included fifteen control points within the survey area. It was found that camera one needed to be placed to the left view of the subject at a point 3.8 meters away from the point of the center of the movement field and at a height of 2.7 meters. Camera two and camera three were placed on the frontal view of the subject at 4.1 meters , and 3.2 meters away from the center of the movement field respectively and at the heights of 2.5 meters, and 2.4 meters respectively. The angles of camera two and camera three were 94 degrees, and 135 degrees respectively from camera one. From the MacReflex motion analysis system, 3-D coordinates were obtained and smoothed utilizing the Butterworth digital filter technique with a 6 Hz cutoff frequency determined by utilizing a residual analysis method. Kinematic variables of the roundhouse kicks, final velocity of the ankle and knee, angular velocity of the knee, the angular velocity of the thigh projected onto the horizontal plane, and the angular velocity of the shank projected onto the horizontal plane were calculated using Microsoft Excel spreadsheet. The average of three trials for each subject under each condition was used for analysis.

3.2 Instrument Validation

3.2.1 Modified Force Plate

The Kistler force plate in Biomechanics Laboratory at Oregon State University was not available to validate the instrumentation of this study. For this reason it was necessary to construct a modified force plate. The dimensions of this force plate were 1.5 cm x 40 cm x 61 cm. This force plate was constructed by sandwiching four PCB piezoelectric transducers between two steel plates. The bottom steel plate was laid horizontally on the level floor and secured in place by a wood frame. The PCB piezoelectric transducers were placed in the four corners of the force plate. The specifications for each of these force transducers are in Table 2. Each force transducer

Table 2.

Force transducer specifications

Position	Right Front	Right Rear	Left Front	Left Rear
Channel	0	1	2	3
Model	208A03	208A03	208A03	208A03
S/N	11553	11541	11551	11552
Range(lbs)	±500	±500	±500	±500
Sensitivity (mV/lb)	10.22	10.41	10.19	10.33
Rise Time (μsec)	10	10	10	10
Input TC (sec)	≥2000	≥2000	≥2000	≥2000
Natural Frequency (kHz)	70	70	70	70

was powered by its own signal conditioning unit (a PCB Piezotronics 484B) which was DC-coupled to utilize the 2000-second time constant of the force transducers. These conditioning units were connected to the terminal accessory board using channels 0 to 3.

3.2.2 Computer Program

A program written in Microsoft QuickBasic was used to collect the force and acceleration data from the seven channels (4 for forces, and 3 for accelerations) via the A-D board Dash-16 at a sampling frequency of 2400 Hz. The A-D board was set at ±10 volts of input range in bipolar mode. The kicking bag with three accelerometers inside was dropped from a variety heights onto the force plate. Conversion of the data was performed using a similar QuickBasic program which converted all of the trial data. A spreadsheet was utilized to subtract the bias values, to plot force-time curves of the force sensors and the accelerometers. The SPSS statistical program was utilized to determine the correlation between the peak forces measured by the force sensors and the peak forces measured by the accelerometers.

3.2.3 Force Measurement Comparisons between the Force Plate and the Accelerometers

When the peak forces measured by the force plate and by the accelerometers were plotted against each other the regression line had the slope of nearly 1 and intercept slightly less than zero. The forces were significantly correlated with $r = .99$. These results are shown in Figure 6. and Table 3.

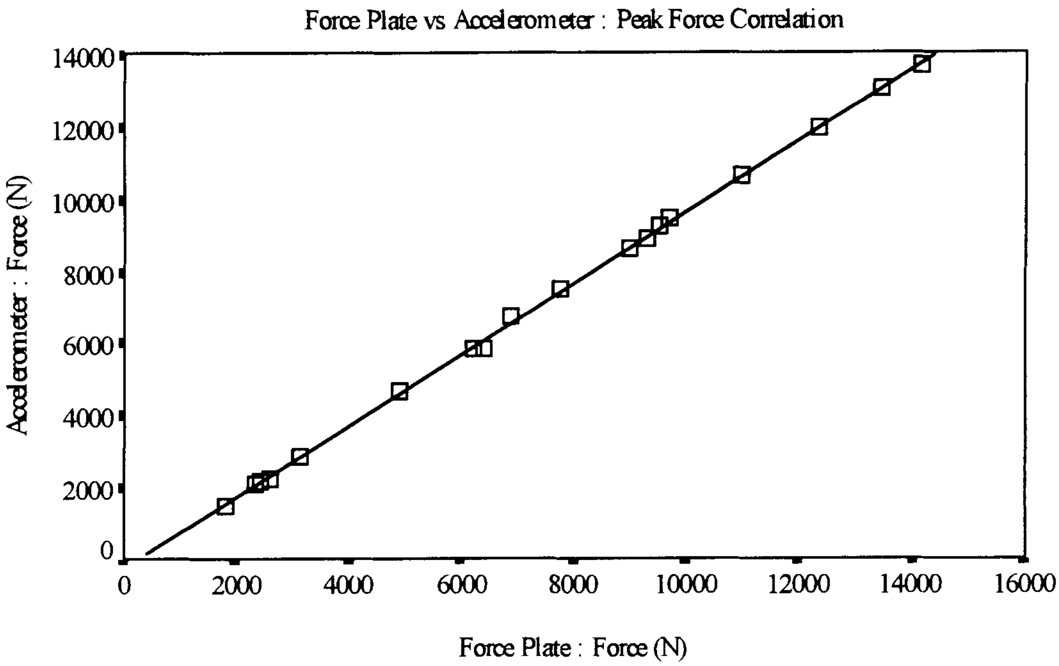

Figure 6. Regression curve for peak forces measured by the force plate versus peak forces measured by the accelerometers. $R^2 = 0.9994$.

Table 3

Regression results: Peak force measured by the force plate versus measured by the accelerometers

Parameter	Value	Std. Error	t- Value	p- Value
Intercept	-256.82	.005	-5.29	<.0001
Slope	0.99			

In addition to peak force, force-time curves measured by the force plate and by the accelerometers were compared over a wide range of impact. These results for three separate trials representing low, medium and high force levels are shown in Figures 7, 8, and 9.

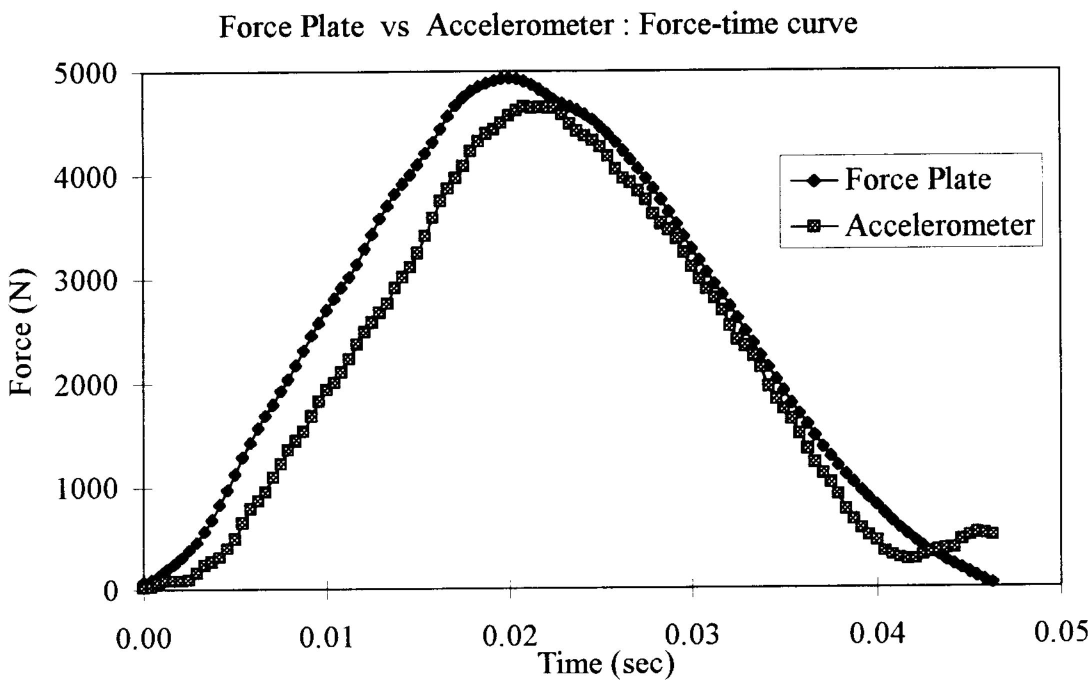

Figure 7. Comparison curves for force plate and accelerometer devices with a low magnitude impact.

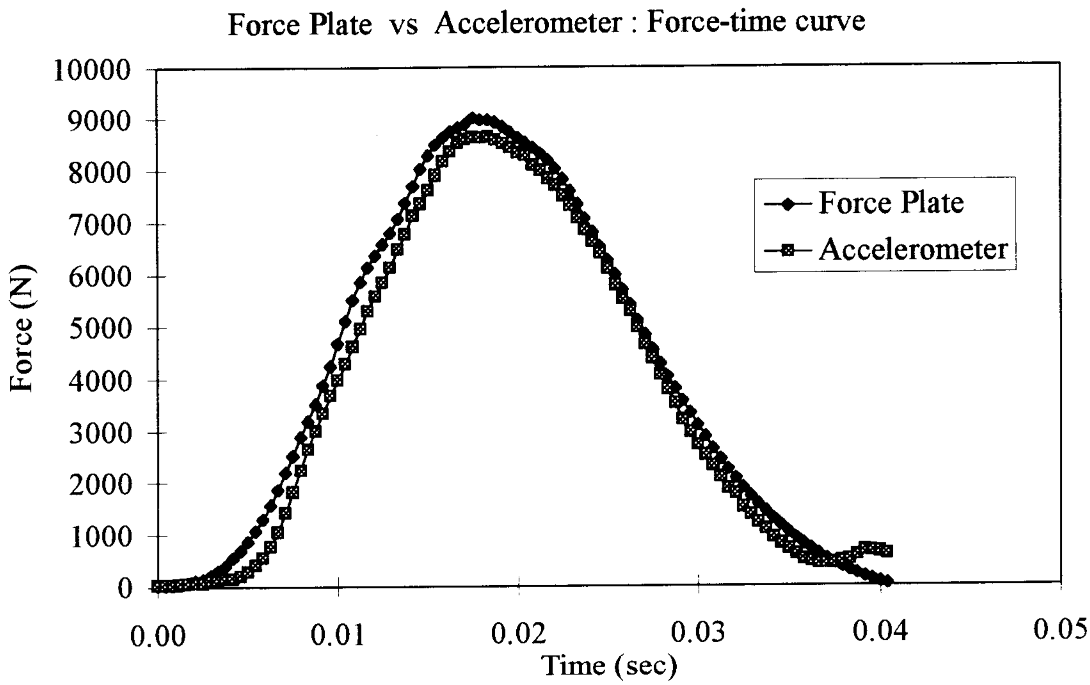

Figure 8. Comparison curves for force plate and accelerometer devices with a medium magnitude impact.

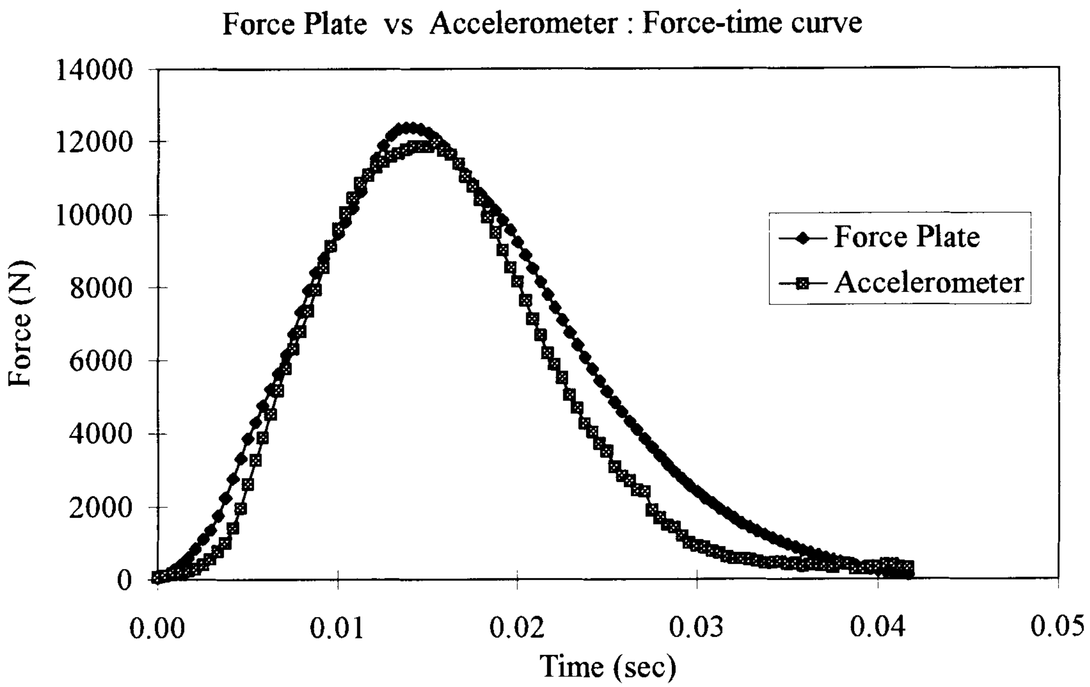

Figure 9. Comparison curves for force plate and accelerometer devices with a high magnitude impact.

In addition, the force measures from the force plate and the corresponding force measures from the accelerometers were compared for each of three trials shown above. The correlations of force measures between both sensors of three trials were 0.98, 0.99, and 0.99 ($p<.05$) respectively. These results are presented in Figures 10, 11, and 12. In all three trials (low, medium, and high magnitude impact), the force plate responded immediately upon the impact of the bag with the force plate, but this was not the case for the accelerometer. The accelerometer only started recording when the force of the impact passed through the bag and cushioning materials to reach the center of the bag at the location of the accelerometer. This time delay depended upon the cushioning material used inside the bag. The softer the materials used in the bag the greater the time delay between the initial force measure by the force plate and the initial acceleration measure. This phenomenon was only observed in the low magnitude impact trials and was not observed in the medium and high magnitude impact trials. Apparently in these cases the delay was too small to be detected by the measurement system. Theoretically, these curves should be straight lines if a solid object was dropped onto the force plate. In this case the curves from those three trials are close enough to being straight lines, so that the results suggest that the use of the accelerometers inside the cushioned bag provide reasonably good force estimation measures. Taken as a whole the validation results indicated that the instrumentation method using triaxial accelerometers provided a very good estimation of the force as it would be measured by a force plate.

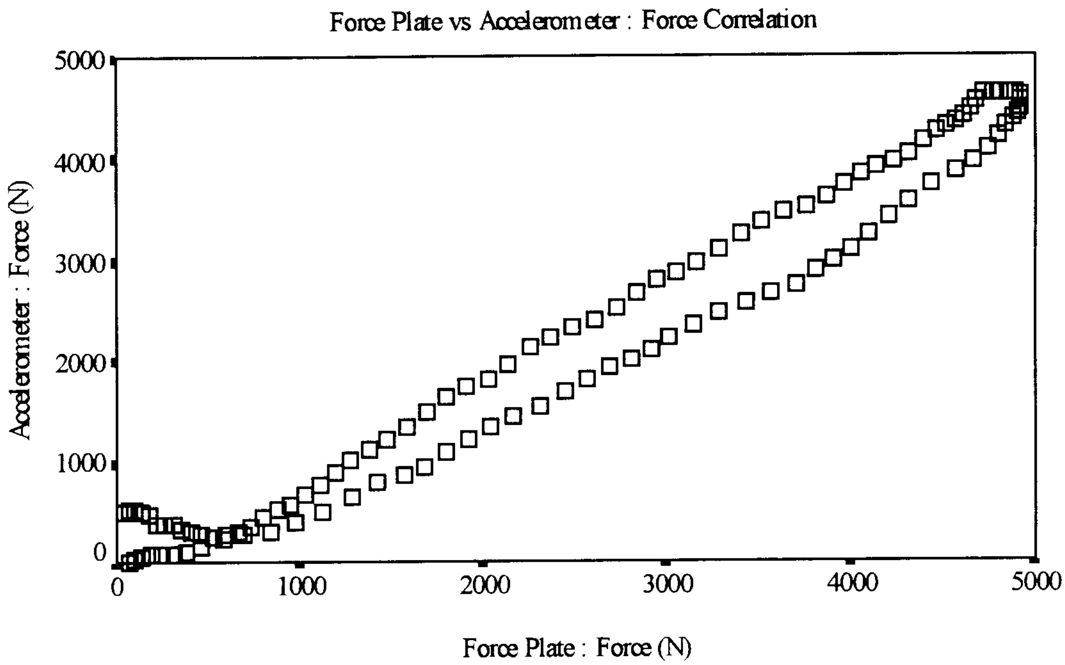

Figure 10. Force measured by the force plate and force measured by the accelerometers from the trial represented in Figure 7. $R^2 = 0.9654$.

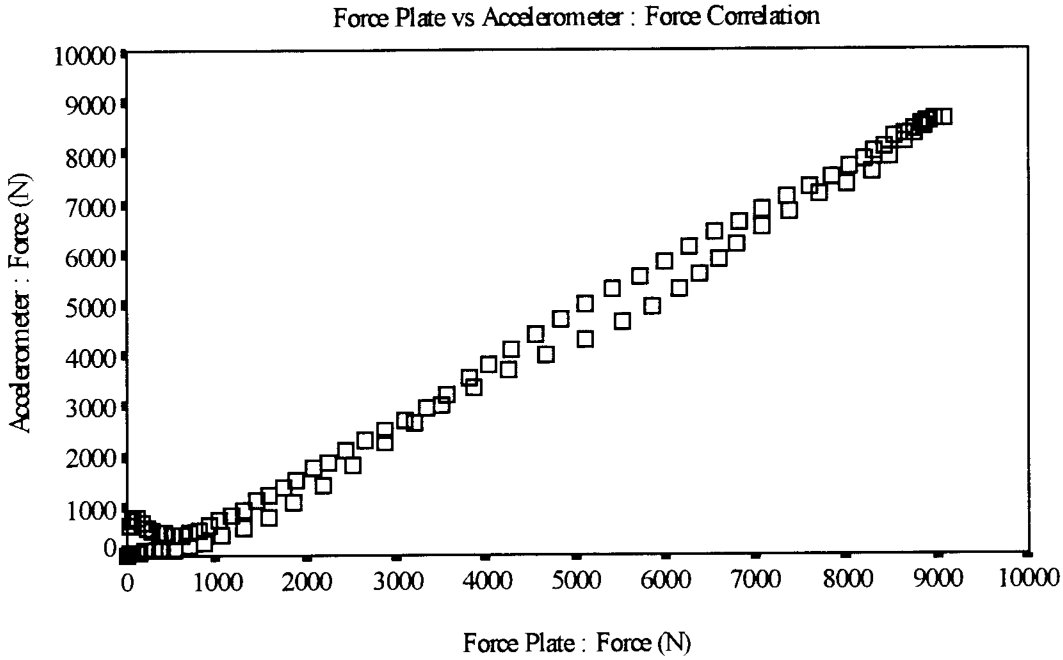

Figure 11. Force measured by the force plate and force measured by the accelerometers from the trial represented in Figure 8. $R^2 = 0.9912$.

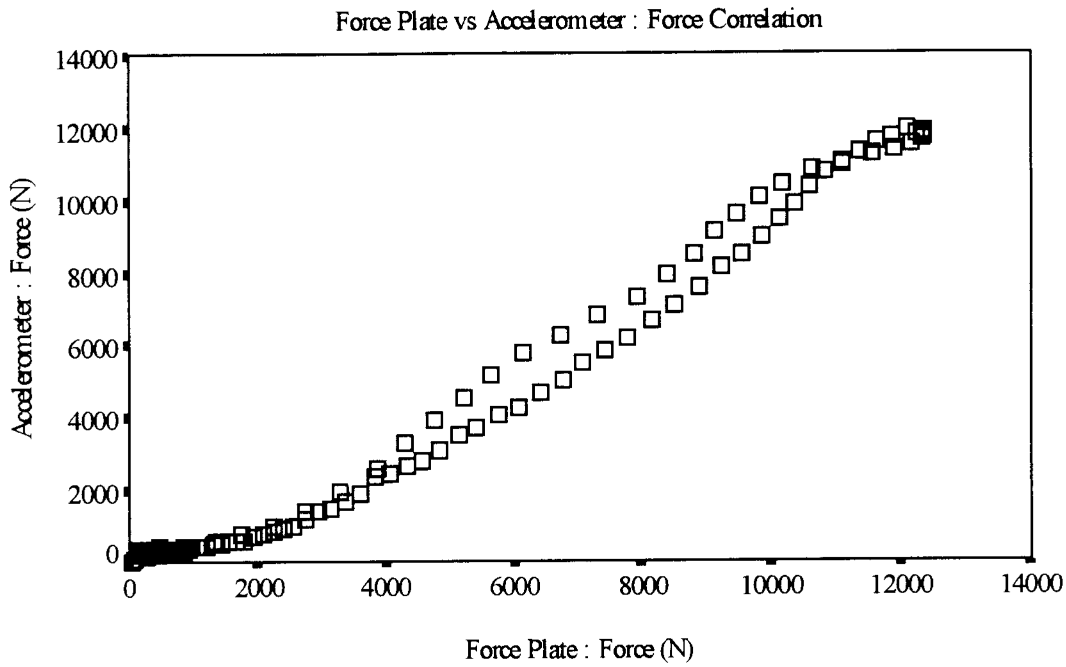

Figure 12. Force measured by the force plate and force measured by the accelerometers from the trial represented in Figure 9. $R^2 = 0.9780$.

3.3.4 Leg Strength Measurements

The speed and strength of the lower extremity are considered to be important factors in the kicking motion in Thai Boxing. After each subject completed his kicking trials he was tested for maximum concentric knee extension and hip flexion, at the Sport Medicine Laboratory. An isokinetic dynamometer was used because it is the preferred method of strength testing during motion because it allows torque to be measured at any point in the range of motion (Perrin, 1993). In this study each subject performed three maximum repetitions of knee extension and hip flexion at 120°/sec on a KinCom isokinetic dynamometer. This speed falls within between the range of test angular velocities (60 and 180 °/s) recommended by Dvir (1995). The average of the peak torque for the three trials were used for analysis.

3.3.5 Subjects

The subjects in this study were ten male Thai Boxing performers from the local area. Their ages ranged from 17 to 24 years old. These subjects' experience in Thai Boxing training ranged from 8 months to 4 years.

The Oregon State University Human Subjects Review, Consent Form, and Institutional Review Board approval are included in Appendix A. Prior to participating in this study, all subjects received and signed the informed consent form. For two of the subjects whose ages were less than 18 years old, informed consent was obtained from the subject's parents.

All of the subjects were asked to provide personal information concerning their age, and number of year of experience in Thai Boxing. In addition all subjects were measured for height, weight, leg strength, and length of kicking leg. All subjects completed the three kicking trials for each of the three height levels of the roundhouse kick.

3.3.6 Procedures for the Data Collection

In order to obtain 3-D coordinates of the roundhouse kicks, a MacReflex motion analysis system consisting of a Macintosh Power PC computer with motion analysis software and three cameras were utilized to determine the kinematic characteristics of each trial. The cameras were placed in appropriate positions to best view the markers. The field of movement of this study was 1.5 meters by 2.0 meters by 1.7 meters (see Figure 13). Five survey poles with fifteen control points were placed one each at the four approximate corners of the movement field and in the center of the field. The 3-D coordinates of the control points were derived from theodolite and survey techniques and then were entered into the MacReflex motion analysis program in order to obtain the 3-D coordinates of the subjects' movement (control point coordinates are shown in Table 4). After deriving the 3-D coordinates of the control points, the survey poles and theodolite were removed.

The kicking bag was hung from a ceiling beam in the Biomechanics Laboratory, Oregon State University. The height of the bag was adjustable and for each subject it was set at three different height levels corresponding to 50%, 100%, and 150% of the leg length of that subject. In order to detect the point in trial when foot contact with the bag was made, a marker was placed on the top of the kicking bag. Acceleration signals from the accelerometers were sent to an ICP battery-powered signal conditioner model 482A16. This signal amplifier was utilized for signal conditioning with a gain of 10 and also connected to a terminal accessory board of the channel 5 to 7. These gain signals were sent to the Metrabyte A-D board Dash-16 and computer for data collection. The gain setting of the A-D board was $\pm$ 5 volts in bipolar mode. The acceleration data were recorded via the A-D board with a QuickBasic program configured to sample at 2400 samples per second.

Prior to the collection of data, the subject order and three kick height levels (low, middle, and high) were randomly assigned. In order to prevent injury to the ankle and foot at the impact point, subjects were allowed to wear an ankle brace. It should be noted that the present study measured velocity using the MacReflex system which tracks markers attached to various points on the body of the subject. It was not feasible to attach a marker to the kicking foot of a subject because of the foot striking the kicking bag. In this study it was also not possible to place markers on the specific anatomical landmarks at the ankle joint of the kicking leg and at the hip joints. The closest point to the foot, where it was possible to attach a marker so that it would not bother the kicker or cause injury, and so that it remained stable during the kick, was located 3-inches above the center of the malleolus on the lateral side of the right ankle. In the case of the hip markers it was not possible to place the tracking cameras to observe the motion of the hip joints. For this reason the hip markers were located slightly above and forward of the hip joints on the illiac crests of the hips. Before warm-up, markers were placed on the following six anatomical landmarks: the center of the patella on the front side of the right knee, the front of the illiac crest of the right and left hips, the distal end of the tibia on the front side of the left ankle, and the distal end of the first metatarsal of the left foot.

After five minutes of required warm-up, subjects were instructed to perform three trials at each height target, and allowed to have 20 seconds rest between each trial and 2 minutes rest between each height level. During each trial of kicking, a computer with A-D conversion was used to determine kinetic characteristics while the MacReflex motion analysis system with 3 cameras operating at 120 frames per second was utilized to record the kicking motion. Immediately following the final kicking trial, the leg strength of the subjects was measured.

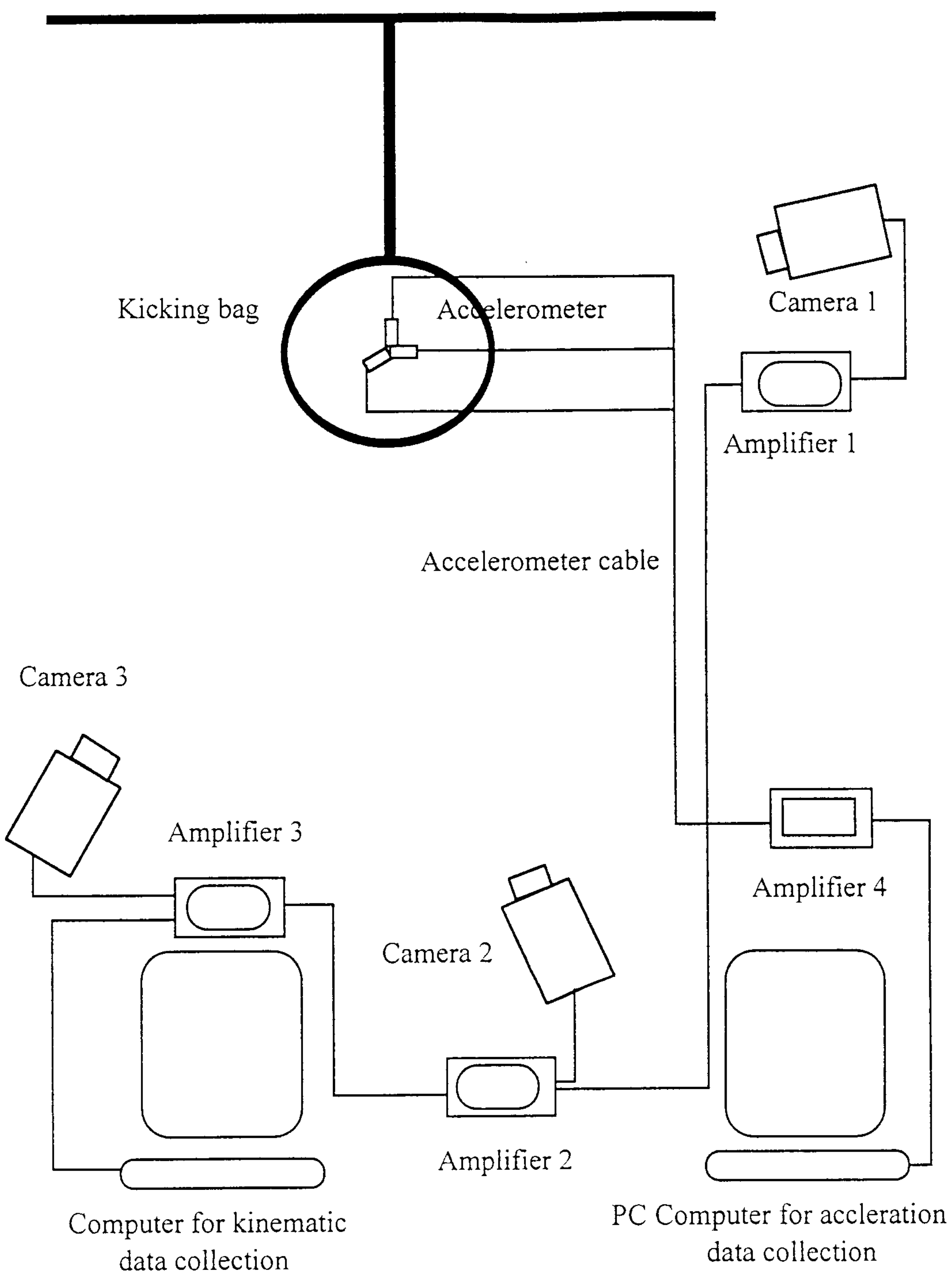

Figure 13. Instrument set for data collection.

Table 4

Coordinates of control point in centimeters

Position\Axis	X	Y	Z
Top1	0	1.62	0
Middle1	0	0.71	0
Bottom1	0	0.10	0
Top2	0.24	1.62	1.35
Middle2	0.24	0.71	1.34
Bottom2	0.24	0.10	1.34
Top3	-1.60	1.62	1.76
Middle3	-1.60	0.71	1.76
Bottom3	-1.60	0.10	1.76
Top4	-1.87	1.62	0.33
Middle4	-1.87	0.71	0.33
Bottom4	-1.87	0.10	0.33
Top5	-0.75	1.62	0.81
Middle5	-0.75	0.71	0.81
Bottom5	-0.75	0.10	0.81

3.3.7 Design

This study utilized a single factor repeated measures design for all conditions for all participants. The independent variable was the height level of kicking (low, middle, and high). The dependent kinetic variables were peak force and impulse. The dependent kinematic variables were final velocity of the ankle and knee, angular velocity of the knee, and the angular velocity of the thigh and the angular velocity of the shank projected onto the horizontal plane at the contact point.

3.3.8 Data Analysis

Anthropometric data for each subject included weight, height, and leg length. The analysis of variance for repeated measured design in SPSS statistical program was employed to compare the peak force, impulse, final velocity of the ankle, and angular velocity of the knee at three different height levels of the roundhouse kicks. Bonferroni post-hoc analyses were performed when significant differences in peak force, impulse, and final velocity of the ankle for the low level, middle level, and high level kicks were detected. The Pearson Product Moment correlation coefficient was used to determine the relationship between the following pairs of variables: leg strength and peak force, leg strength and impulse, final velocity of the ankle and peak force, and final velocity of the ankle and impulse. An alpha level of .05 was selected for the overall F-tests, the post-hoc analysis, and for determining the relationship between variables. When there are so many comparisons in post-hoc analysis, the experiment-wise probability need to be considered. In this study with three comparisons in each variable, peak force, impulse, and final velocity of the ankle, the probability of making a type I error somewhere in the experiment would be greater than .05 of the a priori alpha level. The actual probability determined by $p = (1 - (1 - \alpha/2)^3) \sim .07$ slightly elevated probability of type I error which was deemed acceptable for the topic of this study.

CHAPTER 4
RESULTS AND DISCUSSION

The purpose of this study was to determine a kinetic and kinematic analyses of three height levels of the roundhouse kick in Thai Boxing. This involved determining and comparing the peak force, impulse of the kick, the final linear velocity of the ankle, the linear velocity of the kicking ankle and the knee, the angular velocity of the knee, and the angular velocity of the shank and of the thigh projected onto the horizontal plane. In addition, the study also determined the relationship between leg strength and peak force, between leg strength and impulse, and between final linear velocity of the kicking ankle and the kinetic variables of peak force and impulse.

4.1 Anthropometric Measurements

Anthropometric measurements for each subject are presented in Table 5. The subjects' heights range from 162 cm to 188 cm. The mass for each subject was between 61 kg and 86 kg except for subject #6 who had a mass of 145 kg . The body type of this subject was not similar to the typical Thai boxer, but this subject was a member of the Thai boxing school that provided the subjects and had been training in Thai boxing for more than the required 6 months minimum time. In general, the trial results from this subject did not provide outlier data except the leg strength. The leg length of subjects was between 74 cm to 86 cm. Except for subject #6, the other subjects were similar in their physical characteristics for mass, height, and leg length.

4.2 Leg Strength Measurements

A Kincom isokinetic dynamometer was used to measure the peak isokinetic torque of knee extension of the subject's kicking leg, and the peak isokinetic torque of hip flexion at 120° per second. Subjects' leg strength measurements are presented in Table 6. The mean and standard deviation of the peak isokinetic torque for knee

Table 5
Anthropometric information and experience in Thai Boxing of the subjects

Subject	Mass (Kg)	Height (cm)	Leg length (cm)	Experience (month)
1	68	168	79	36
2	72	180	84	30
3	72	180	84	48
4	75	177	85	36
5	72	180	85	36
6	145	188	86	8
7	75	167	79	12
8	61	162	74	10
9	75	182	86	9
10	86	175	84	10
Mean	80	176	83	23
S.D.	23.6	8.0	3.9	15.1

Table 6
Individual subject means for peak isokinetic torque of the kicking leg at a speed of 120 °/sec

Subject	Knee Extension (Nm)	Hip Flexion (Nm)
1	149.5	139.6
2	203.6	177.5
3	215.0	121.0
4	175.7	160.8
5	180.7	176.6
6	267.8	252.5
7	166.7	129.6
8	168.0	163.1
9	199.9	134.6
10	211.4	137.8
Mean	193.8	159.3
S.D.	33.7	38.2

extension was 193.8±33.7 Nm respectively. The mean and standard deviation of the peak isokinetic torque for hip flexion was 159.3±38.2 Nm respectively.

In comparison to other kicking studies, the means of the peak isokinetic torque of both knee extension and hip flexion for the Thai boxers in this study were somewhat greater than those previously found for elite soccer players. Poulmedis (1985) measured peak isokinetic torque of knee extension and hip flexion for soccer players at a speed of 90°/sec. His results were 191±35 Nm and 129±27 Nm respectively.

4.3 Kinetic Results

4.3.1 Mean Peak Force

The mean peak forces of the roundhouse kick at the low level and middle level were significantly greater than the mean peak force at the high level ($p<.05$). The values of the mean peak forces and standard deviations for low level, middle level, and high level kicks were 6702±3514 Newtons, 7420±3477 Newtons, and 5618±3253 Newtons respectively. There was no significant difference in mean peak force between the low level and middle level kicks. Individual subject's mean peak forces for each height level are shown in Figure 14. In figures 14 through 16, the subjects have been ordered from 1 to 10 based on the middle level kick magnitude.

The mean peak force of the roundhouse kick at three different height levels ranged from 2,071 Newtons to 14,024 Newtons for the subjects in this study. The kicks at the low level and middle level generated greater peak force than the high level kicks ($p<.05$). However, there was no significant difference in mean peak force generated between the low level and middle level kicks. With respect to the high level kick this agrees with Hypothesis that the higher level kicks would generate lower values for peak force than the lower level kicks, but in comparing the middle level and low level kicks this Hypothesis was not confirmed. One explanation for these findings is that the targets for the low level and middle level kicks were approximately at the knee height and the hip height of each subject while the target of

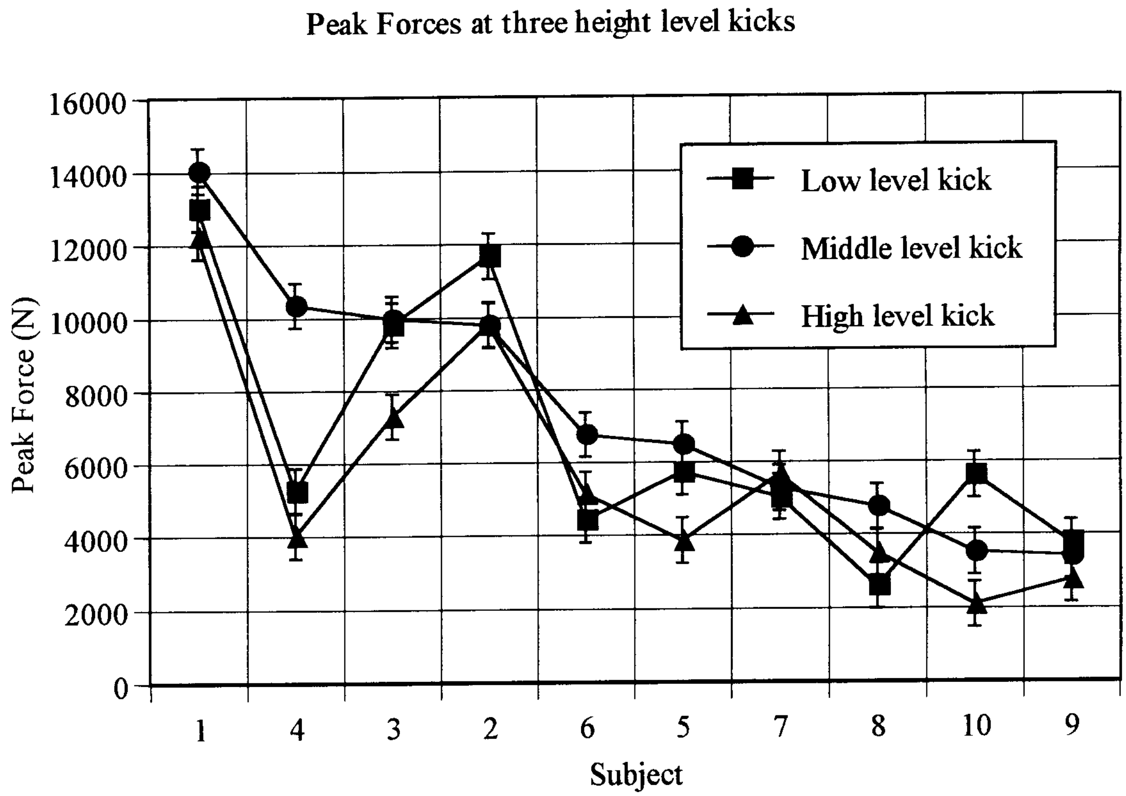

Figure 14. Individual subjects' mean peak forces at three different height levels.

the high level kicks was approximately at the shoulder height. The main factors affecting the mean peak force differentiation at each height level should be : a) the external force (ground reaction force) acting on both the kicking foot during push off and on the supporting foot throughout the kick, b) the body orientation throughout the kick, and c) the final velocity of the kicking foot.

For this study the subjects were right footed kickers, the left foot and leg provide the pivot point and the total support for the body during the kick. In a previous Taekwondo study there was no significant difference in the ground reaction force provided by the supporting foot for three different styles of front kick (Park, 1989). Based on this result it is likely that there is no significant difference in the ground reaction force with respect to the supporting foot among the three height levels of Thai boxing roundhouse kick. Measuring ground reaction force was not an objective of this study, however, if Park's finding in this area is also true for the Thai boxing roundhouse kick, this factor would not provide an explanation for the present findings concerning the relative peak force of the different height level roundhouse kicks. However, in Thai boxing to generate more momentum of the kicking leg the boxer can also push off of the kicking foot as he begins the kick. For each kick, any difference in the push off action of the kicking foot should result in a difference in the maximum ground reaction force. This would cause a difference in peak force at the impact. This factor may be important in explaining the differences in peak force at the different kick heights, however, there are no previous studies concerning the ground reaction force of the push off of from the kicking foot. Future kicking studies should look for any difference in the push off the kicking foot for different height level kicks.

The body orientation during kicking is another factor that affects the magnitude of the peak force at the impact. The low level and middle level kick targets in the present study were similar to the targets used in studies of karate kicks (Jordan, 1973, Powell, 1989) and Taekwondo kicks (Park, 1989). These target levels facilitate the subject having an appropriate body orientation to generate the force from the planting foot through the hips and through the kicking foot. On the other hand, during the high level kick the boxer's approach to the shoulder level target requires the upper body to lean backwards to maintain overall balance as the kicking foot is extended toward the high level target. The hip and knee level kicks do not require this same body adjustment to maintain balance. The total system momentum of each kick is based on sum of the products of the mass and the velocity of each segment. The factor of mass does not change for the three kicking levels. The velocity of each body segment is a vector with both magnitude and direction components. The backwards direction of the upper body segment vector during the high level kick will consume a portion of this whole body system momentum with the result that there is less momentum in the system that is associated with the kicking foot. This factor would explain why less peak force was generated from the high level kick as compared to the low level and middle level kicks.

Body mass is another factor that should affect the magnitude of the peak force if the body mass is utilized in delivering the kick. That is, the subject with a large body mass should have the potential to deliver a kick with greater peak force than the subject with a small body mass. However, this study found that there was no significant correlation between the body mass and peak force. This results suggested that the total body mass did not affect the magnitude of the peak force. There are two possible reasons for this result. Since force is the product of mass times acceleration, one possibility is that the boxers with larger body mass produce less acceleration of the kicking leg in the roundhouse kick. The second possibility is that the total body mass is not utilized in delivering the kick. That is, only a portion of the total body mass is effectively used for the body segments that deliver the kick.

The final velocity of the kicking foot is another factor that should affect the magnitude of the peak force at the point of contact. This has been shown in a karate kicking study (Powell, 1989). The present study found a positive relationship between the mean final velocity of the kicking ankle and mean peak force, $r = 0.89$ ($p<.05$). The final velocity of the kicking ankle was highest for the middle level kick and lowest for the high level kick, however, there was no significant difference in the final velocity of the kicking ankle among the three height level kicks. That is, for the roundhouse kick in Thai boxing the final velocity of the kicking ankle is not significantly different for the different kick height levels. For this reason the final velocity of the kicking ankle does not explain the difference in peak force at the different kick height levels.

4.3.2 Mean Impulse

The mean impulse of the roundhouse kick at the middle level was significantly greater than the mean impulse at the high level ($p<.05$). The values of the mean impulses and standard deviations for the low, middle, and high level kicks were 42.9 ± 15 Newton-seconds, 50.2 ± 19 Newton-seconds, and 40.6 ± 16 Newton-seconds respectively. There were no significant differences in the mean impulse between the low level and high level kicks, and between the low level and middle level kicks. Individual subject's mean impulses at each height level is shown in Figure 15.

The mean impulse was the highest for the middle level kick and lowest for the high level kick. In this case the high level kick condition shows agreement with Hypothesis that the higher level kicks would generate lower values for impulse than the lower level kicks, but in comparing the low level and middle level kicks, and the low level and high level kicks this Hypothesis was not confirmed. Because impulse is partially determined by peak force this result is not unexpected given the findings for comparing the peak force of the three levels.

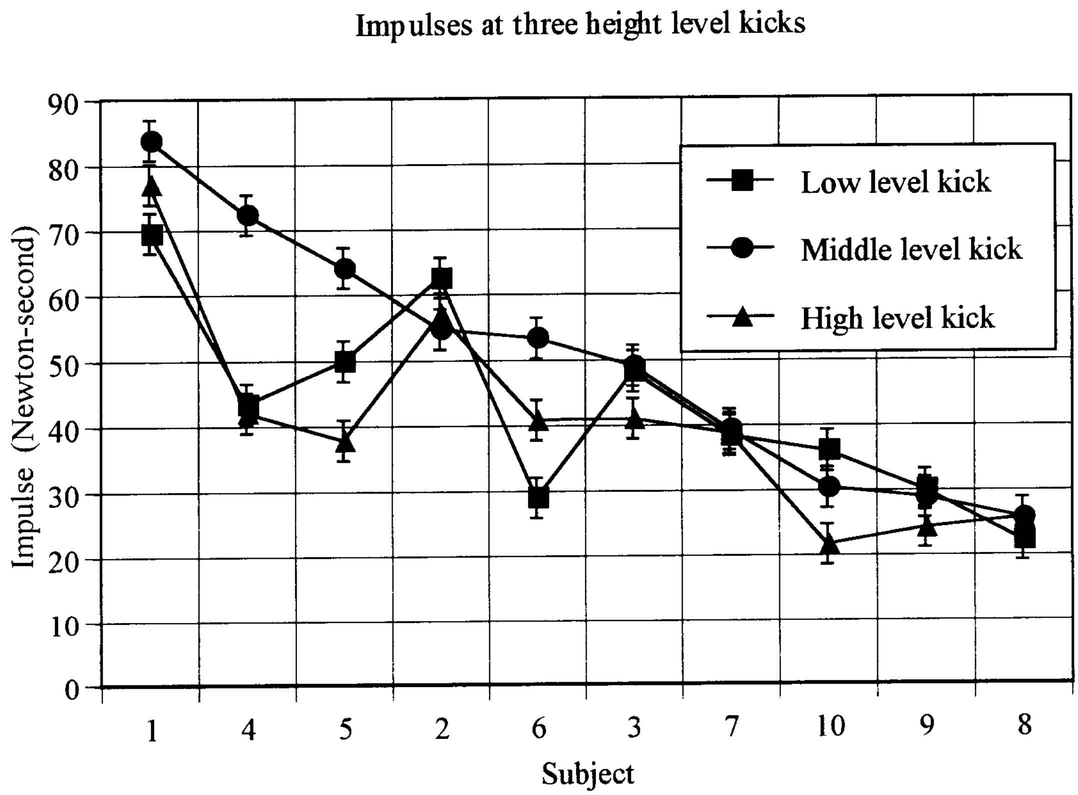

Figure 15. Individual subjects' mean impulses at three different height levels.

4.4 Kinematic Results

4.4.1 Mean Final Linear Velocity of the Kicking Ankle

The mean final linear velocity of the ankle at impact for the low, middle, and high level of the roundhouse kicks were 6.9±0.8 m/s, 7.1±1.1 m/s, and 6.8±1.2 m/s respectively. These results were consistent with the findings of the ordering of the peak force at the three height levels, but the final velocities were not significantly different at the .05 level.

The mean final velocities of the ankle at impact of this study were similar to a Taekwondo kicking study, but greater than that of karate kicks studies. In the Taekwondo study the mean final velocities of the foot ranged from 6.9 m/s to 7.5 m/s for three types of front kick (Park, 1989). In the karate studies, the mean final velocities of the foot were 5.2 m/s, 6.5 m/s, and 5.5 m/s respectively for the side kick, back kick, and front thrust kick (Jordan, 1973), and 3.8 m/s, 4.3 m/s, and 4.7 m/s respectively for the snap side kick, modified snap side kick, and thrust side kick (Powell, 1989).

Individual mean final velocities of the ankle at each height level are shown in Figure 16. In Figure 16 the subjects have been ordered from 1 to 10 based on the magnitude of each subject's middle level kick.

It was hypothesized that the mean final velocity of the ankle would be greatest for the lower level kicks relative to higher level kicks. The results did not confirm this hypothesis. The low level kick actually had a lower final velocity than the middle level kick although this difference was not statistically significant. In determining final velocity of the kicking ankle, the major contribution probably comes from the motion of the other body parts such as the pivoting of the supporting foot, the turning of the hips and trunk, and the swinging of the arms (Young, 1991). The present study of Thai boxing suggests that there is no significant difference in the effectiveness of the technique of the roundhouse kick in terms of mean final velocity of the ankle at the different kick height levels.

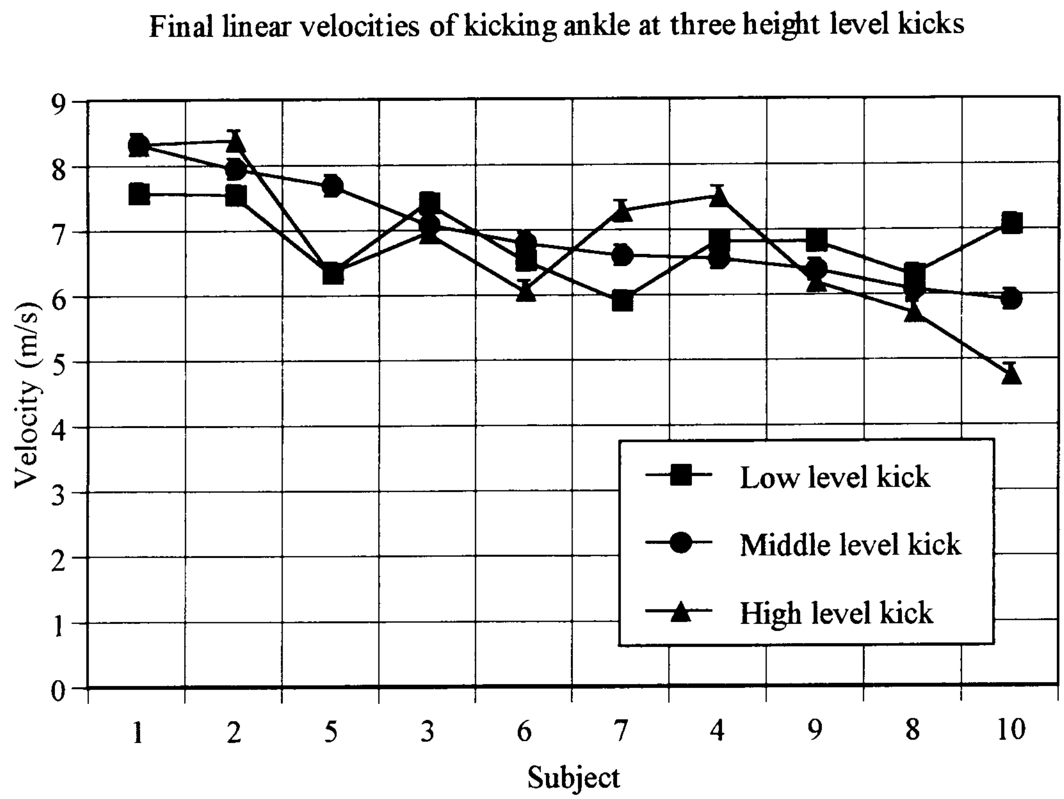

Figure 16. Individual subjects' mean final linear velocity of the kicking ankle at three height levels.

4.4.2 Linear Velocity of the Kicking Ankle at the Low Level, Middle Level, and High Level Kicks

The values of final velocity of the ankle at impact for low level, middle level, and high level kicks were 6.9±0.8 m/s, 7.1±1.1 m/s, and 6.8±1.2 m/s respectively. The values of maximum velocity of the ankle for low level, middle level, high level kicks were 10.2±0.5 m/s, 10.3±0.6 m/s, and 10.0±0.8 m/s respectively. These values are lower than the maximum foot velocity (11.0-11.3 m/s) found for three types of Taekwondo front kicks (Park, 1989). It should be noted that the present study measured velocity using the MacReflex system which tracks markers attached to various points on the body of the subject. It was not feasible to attach a marker to the kicking foot of a subject because of the foot striking the kicking bag. The ankle was the closest point to the foot where it was possible to attach a marker so that it would not bother the kicker and so that it remained stable during the kick. For this reason this study measured the maximum velocity of the kicking ankle rather than the foot. Since the foot is at the end of the body segment relative to the ankle, the foot should have a greater velocity than that measured for the ankle.

The patterns of linear velocity of the ankle were observed over a period of 120 μsec prior to impact for each of the three height level kicks (Figure 17). For all three kick height levels the linear velocity of the ankle reached the maximum velocity at 48 μsec prior to the point of contact. In comparison, Taekwondo front kicks have been shown to reach maximum velocity from 31 μsec to 42 μsec prior to the point of contact. In this study found that the linear velocity of the kicking ankle drop off is small for the best performer. These results suggested that a good kicking technique involved little decrease of velocity. Kicking involves a sequential swinging motion of connected body segments. The most efficient kicking performance would achieve the maximum velocity at the end of the kinematic chain of body segments at the exact moment of impact. This would provide the greatest momentum and therefore result in the greatest force against the kicking object. In practice it is difficult for human performers to achieve this objective of reaching maximum velocity exactly at the point of impact. This phenomenon has also been found in other sport studies (Gheluwe & Hebbelinck, 1983, Park, 1989).

The patterns of the linear velocity for the low level, middle level, and high level kicks of 10 subjects are shown in Figures 18, 19, and 20.

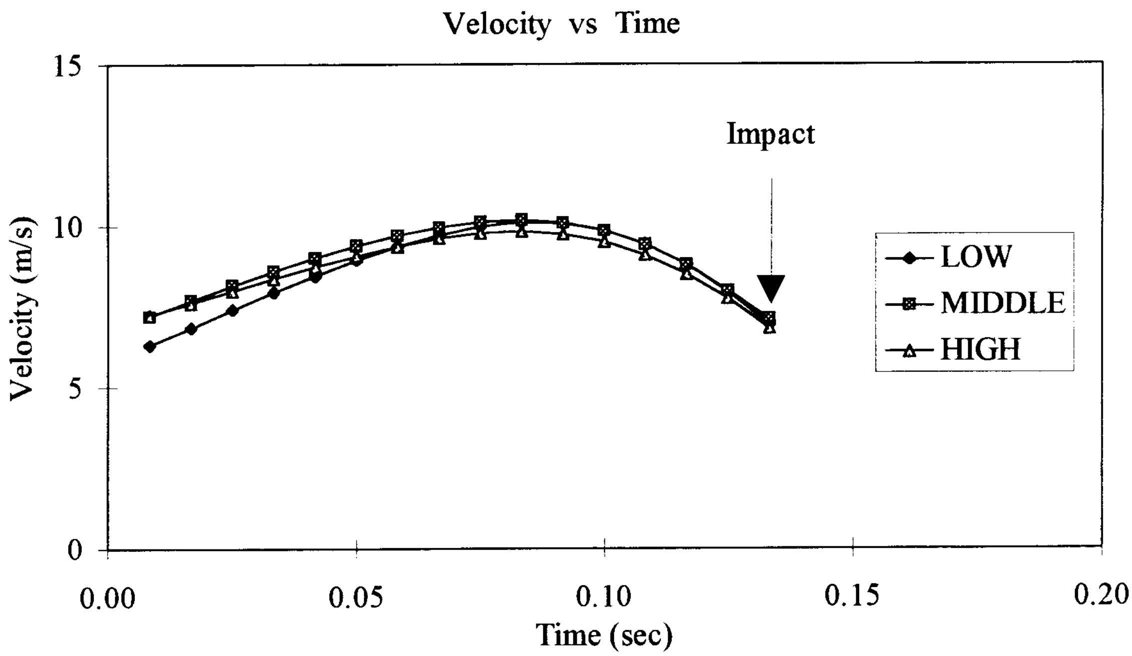

Figure 17. The linear velocity of the ankle at the low level, middle level, and high level kicks.

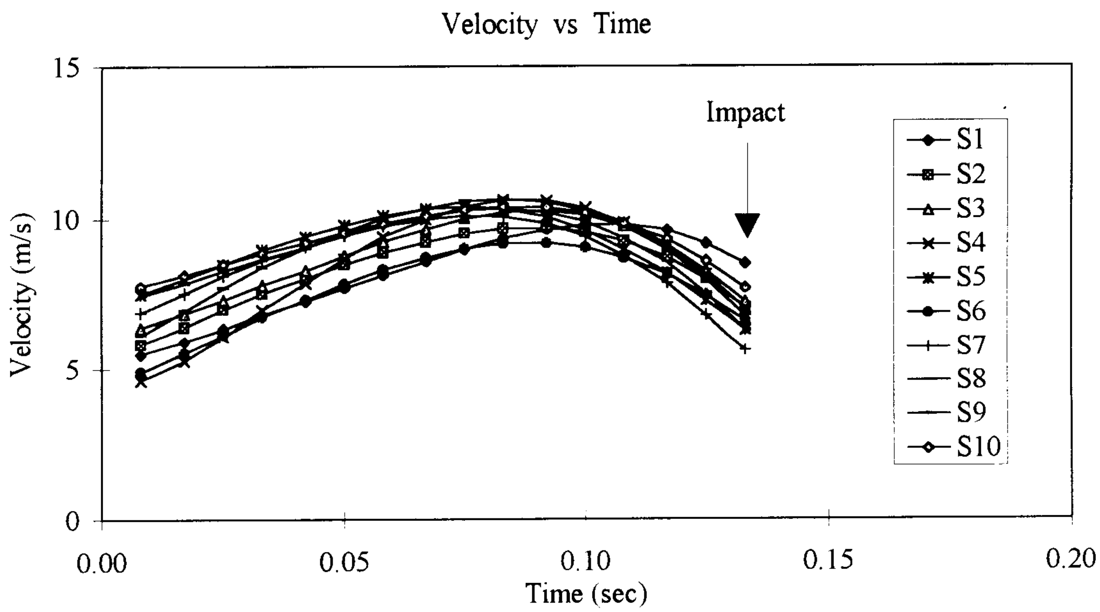

Figure 18. The linear velocity of the ankle at the low level kicks.

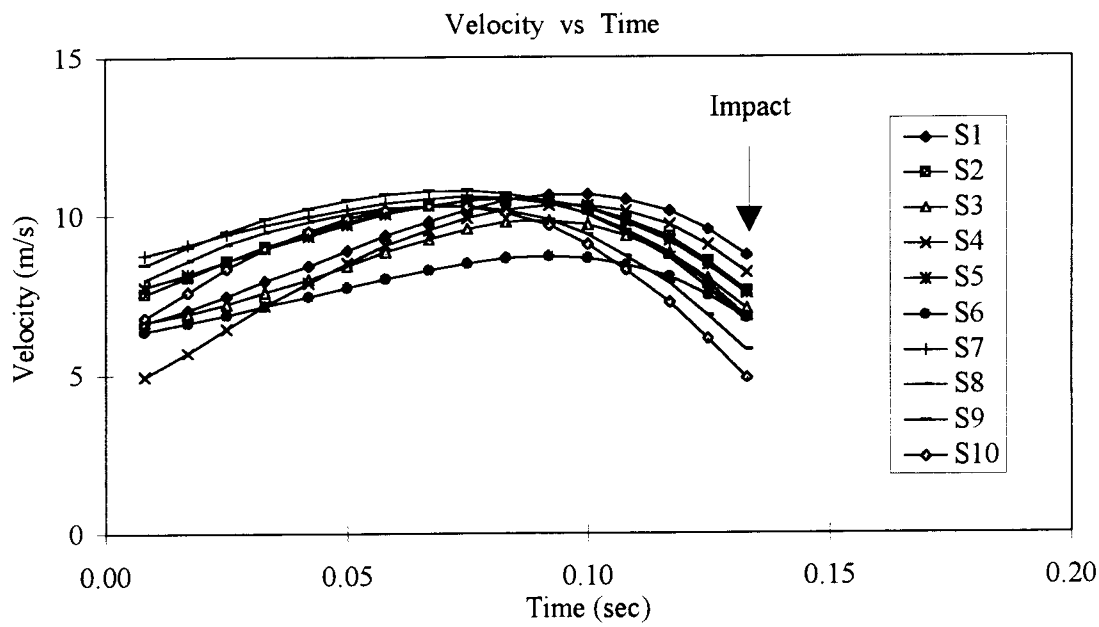

Figure 19. The linear velocity of the ankle at the middle level kicks.

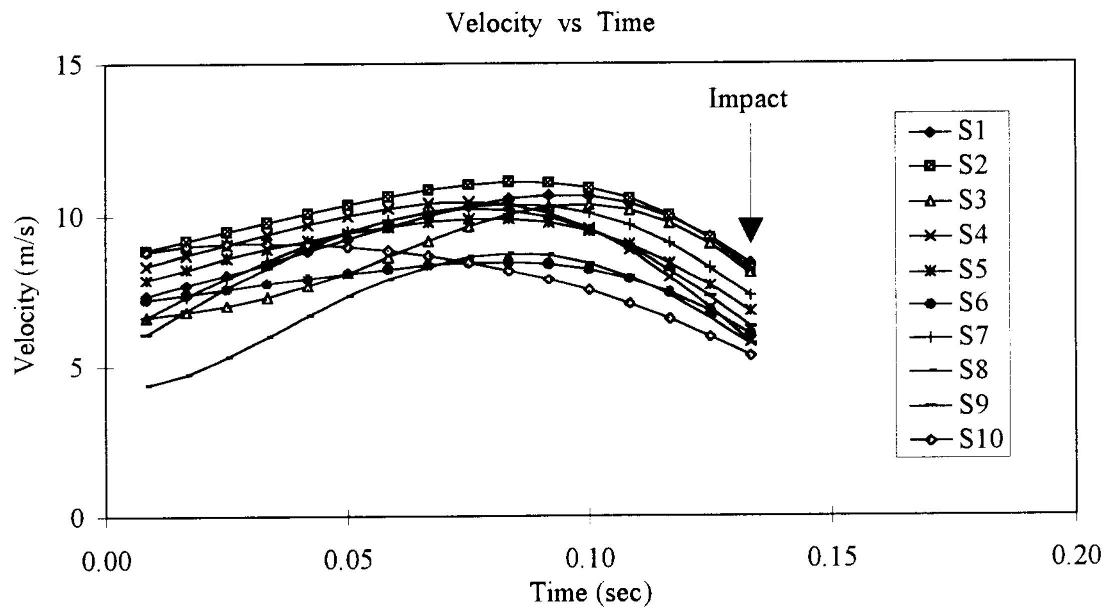

Figure 20. The linear velocity of the ankle at the high level kicks.

4.4.3 Linear Velocity of the Knee at the Low Level, Middle Level, and High Level Kicks

The patterns of linear velocity of the knee were observed over a period of 152 μsec prior to impact for each of the three height level kicks (Figure 21). The linear velocity of the knee for low level, and middle level kicks reached the maximum values at the same time (80 μsec) while the high level kick the maximum value occurred at 96 μsec prior to the impact. The values of maximum velocity of the knee for low level, middle level, and high level kicks were 6.7±1.2 m/s, 7.2±0.8 m/s, 7.3±1.2 m/s respectively. The values of velocity of the knee for low level, middle level, and high level kicks at the impact were 3.3±0.7 m/s, 3.3±0.6 m/s, and 2.6±0.5 m/s respectively. In all three height level kicks, the maximum linear velocity of the knee occurred prior to the maximum linear velocity of the ankle. The patterns of the linear velocity of the knee for the low level, middle level, and high level kicks of 10 subjects are shown in Figures 22, 23, and 24.

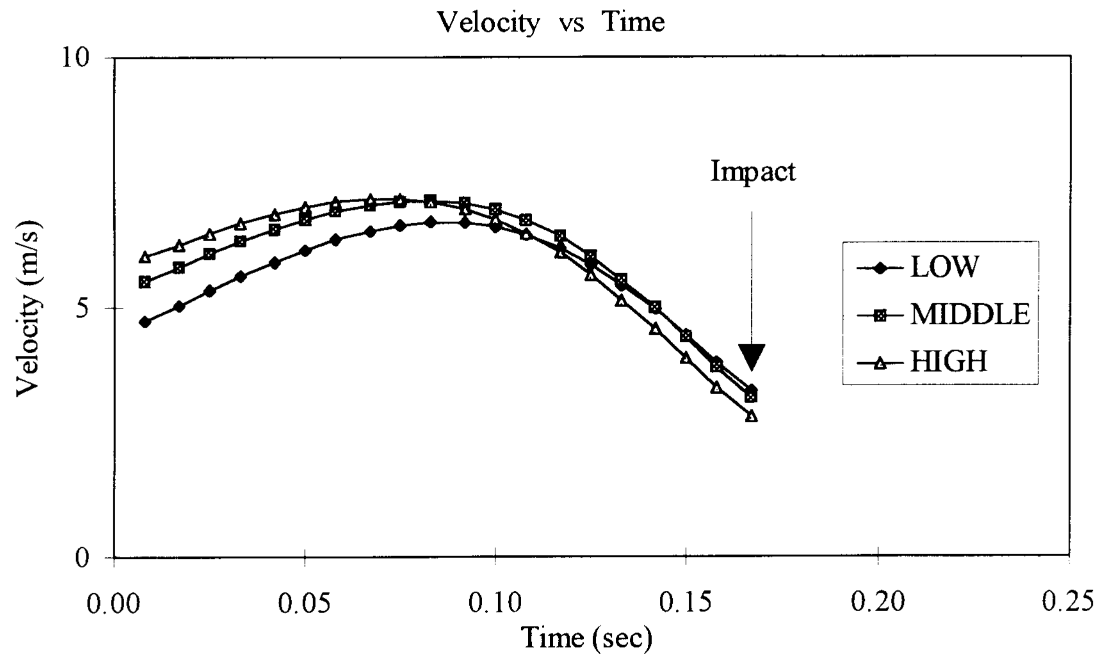

Figure 21. The linear velocity of the knee at the low level, middle level, and high level kicks.

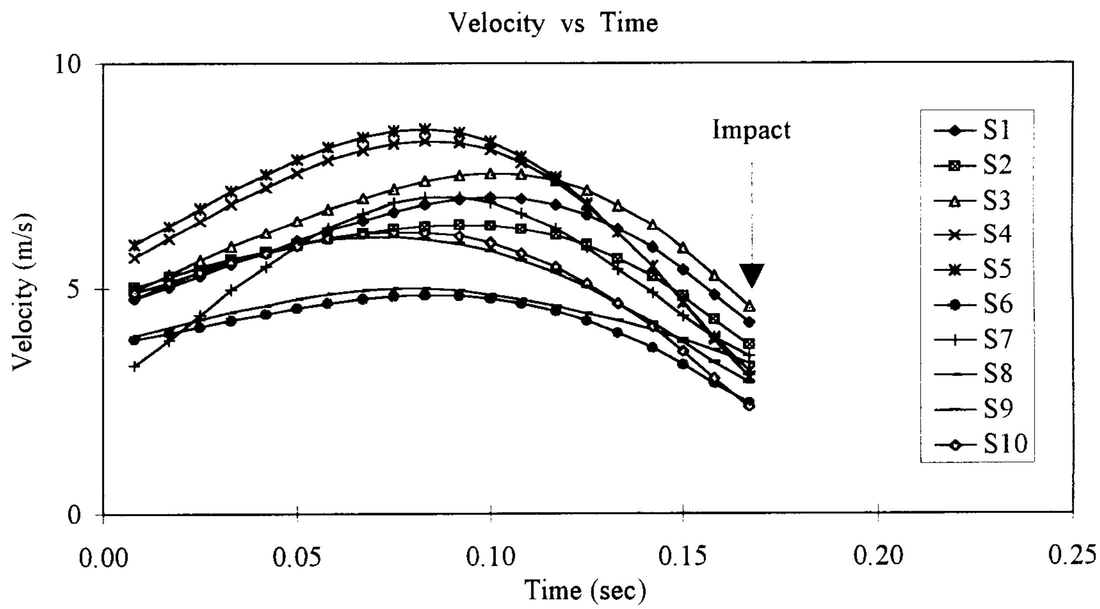

Figure 22. The linear velocity of the knee at the low level kicks.

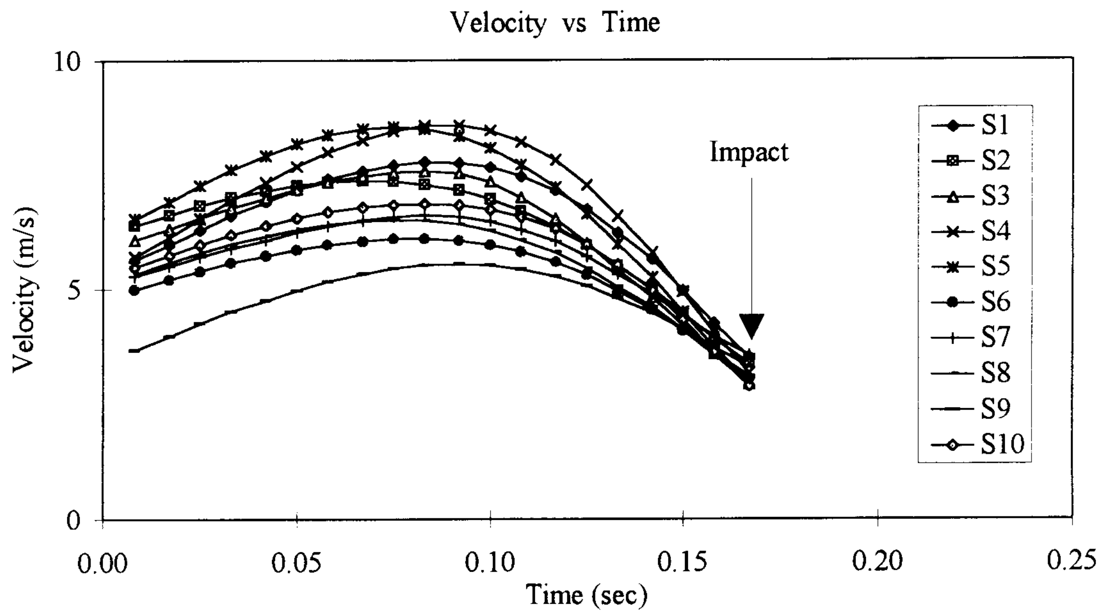

Figure 23. The linear velocity of the knee at the middle level kicks.

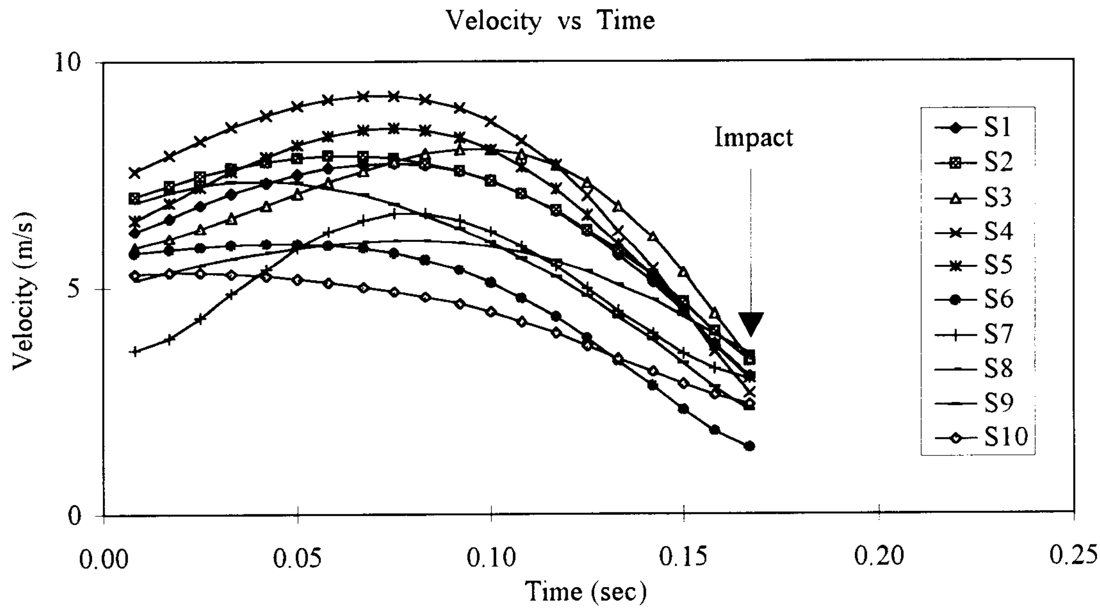

Figure 24. The linear velocity of the knee at the high level kicks.

4.4.4 Angular Velocity of the Knee at Three Different Height Level Kicks

The pattern of angular velocities of the knee were observed for 120 μsec before the impact. The patterns of the angular velocity of the knee for the low, middle and high level kicks are shown in Figure 25. The angular velocity of the knee reached the maximum value at 32 μsec, 24 μsec, and 24 μsec prior to the impact for the low level, middle level, and high level kicks respectively. The maximum angular velocity of the knee for the low level, middle level, and high level kicks were 12.6±3.9 rad/s, 11.8±1.9 rad/s, and 12.1±2.8 rad/s respectively. The values of the angular velocity of the knee at impact were 7.1±1.5 rad/s, 7.7±3.6 rad/s, and 9.5±3.0 rad/s respectively. The patterns of the linear velocity of the knee for the low level, middle level, and high level kicks of 10 subjects are shown in Figures 26, 27, and 28.

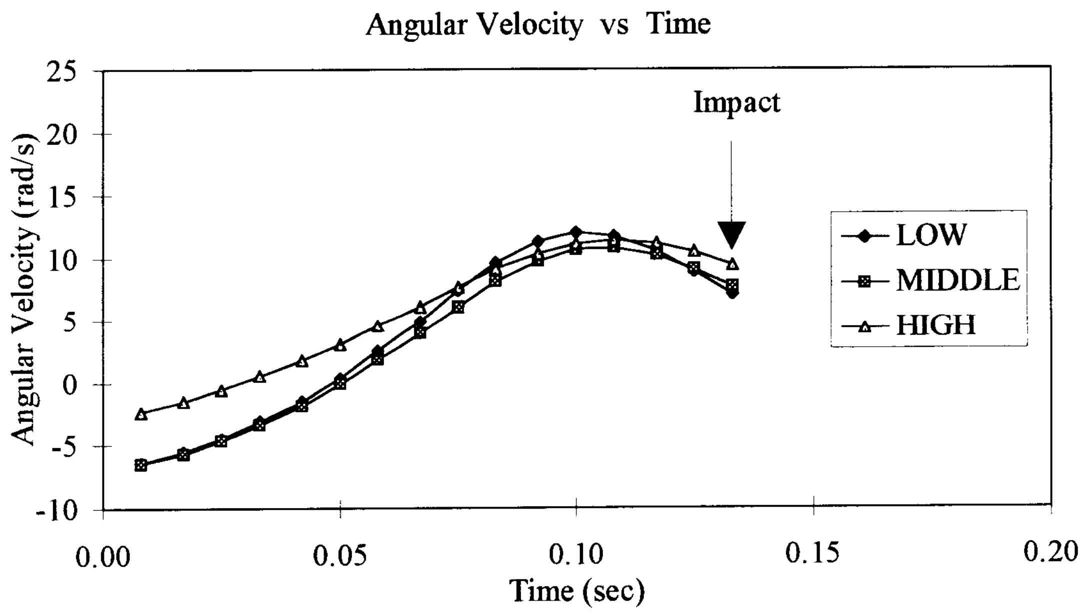

Figure 25. Angular velocity of the knee at the low level, middle level, and high level kicks.

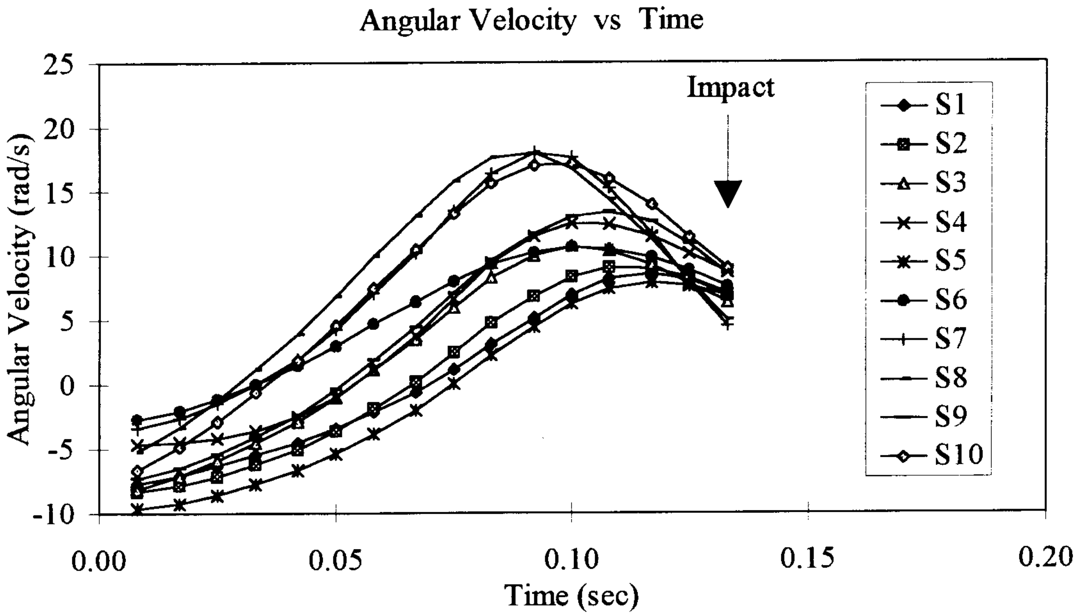

Figure 26. Angular velocity of the knee at the low level kicks.

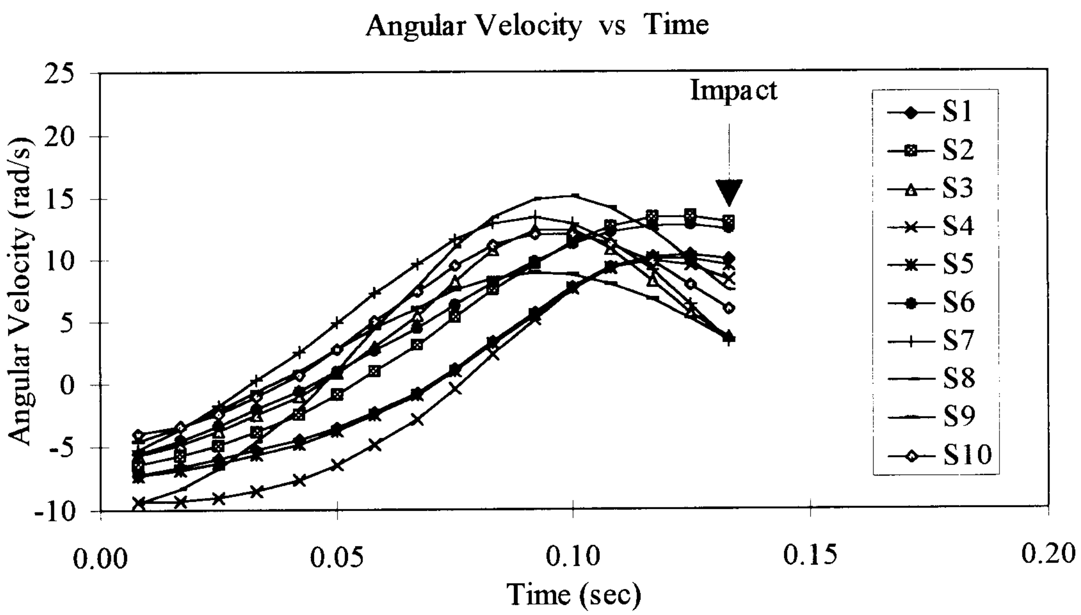

Figure 27. Angular velocity of the knee at the middle level kicks.

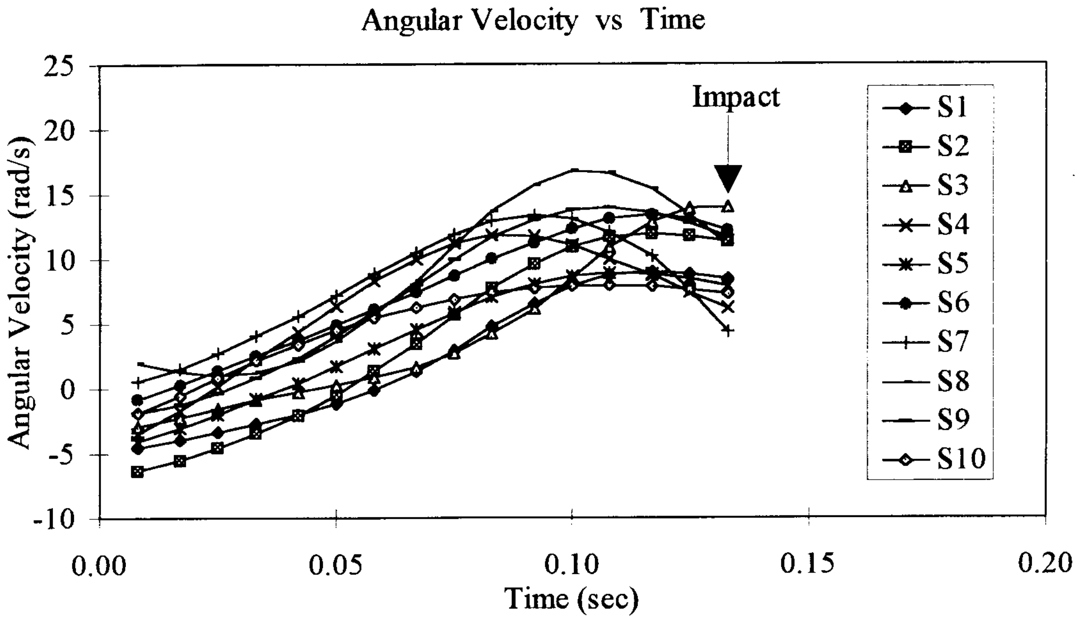

Figure 28. Angular velocity of the knee at the high level kicks.

4.4.5 Angular Velocity of the Shank Projected onto the Horizontal Plane for the Low Level, Middle Level, and High Level Kicks

The angular velocity of the shank projected onto the horizontal plane was observed during the period of 120 μsec prior to the impact for the low level, middle level, and high level kicks. These shank angular velocities are shown in Figure 29. Angular velocity of the shank reached a maximum value at 32 μsec, 40 μsec, and 56 μsec prior to the impact for the low level kick, middle level, and high level kick respectively. The shank reached the maximum angular velocity later than the thigh. This result followed the sequential pattern of a kicking motion or swinging motion as found in previous studies (Elliott, Marsh, & Blanksby, 1986, Gheluwe, 1983, Park, 1989, and Tant, 1990). The maximum angular velocity of the shank projected onto the horizontal plane for low level, middle level, and high level kicks was 21.2±2.3 rad/s, 20.2±2.7 rad/s, and 20.4±3.8 rad/s respectively. These values were lower than the angular velocity of the shank (23.4-24.0 rad/s) in a Taekwondo front kick study (Park, 1989). At impact, the angular velocities were 12.7±2.5 rad/s, 12.5±3.7 rad/s, projected onto horizontal plane for the low level, middle level, and high level kicks of 10 subjects are shown in Figures 30, 31, and 32.

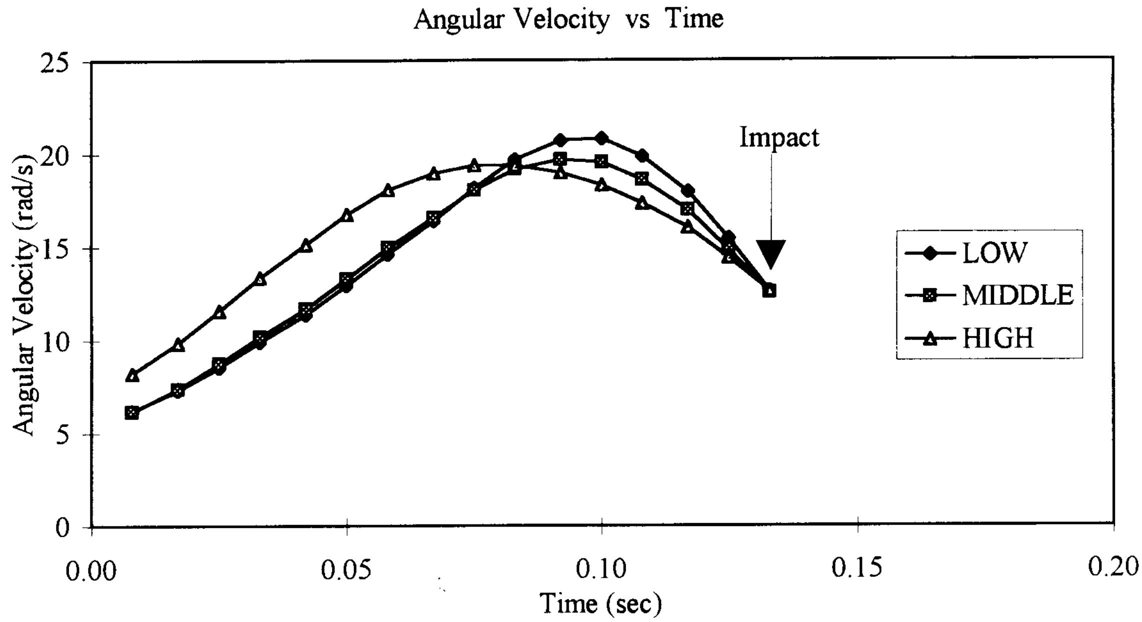

Figure 29. Angular velocity of the shank projected onto the horizontal plane at the low level, middle level, and high level kicks.

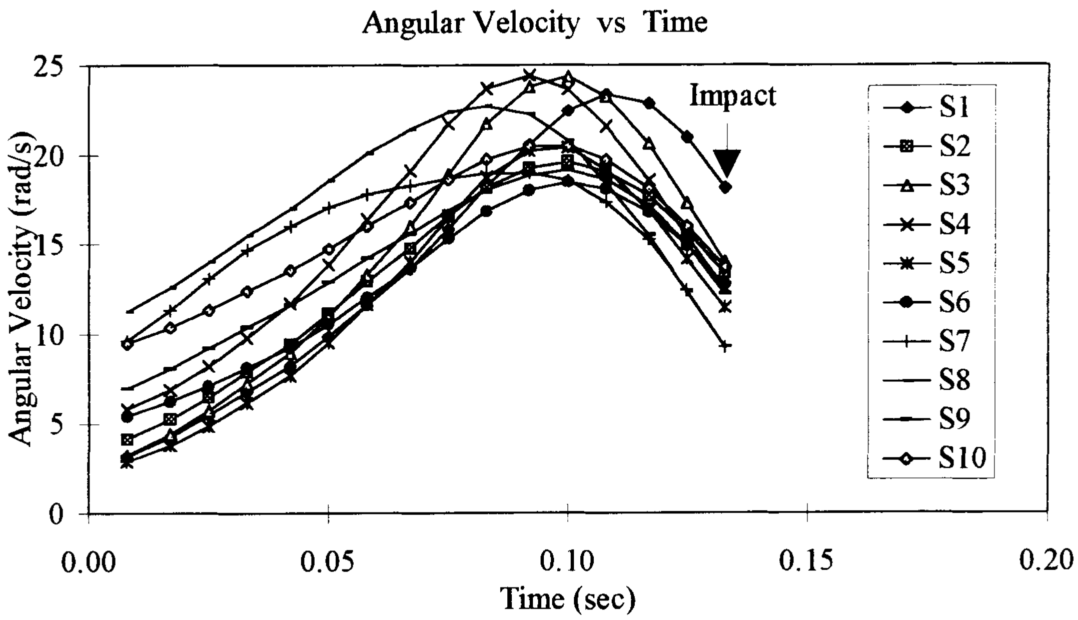

Figure 30. Angular velocity of the shank projected onto the horizontal plane at the low level kicks.

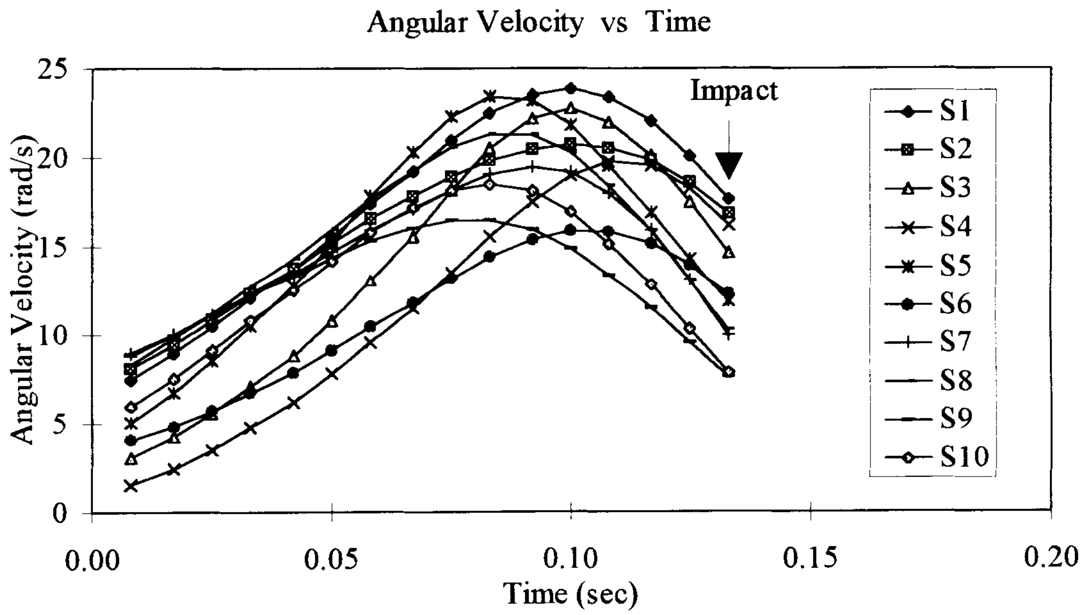

Figure 31. Angular velocity of the shank projected onto the horizontal plane at the middle level kicks.

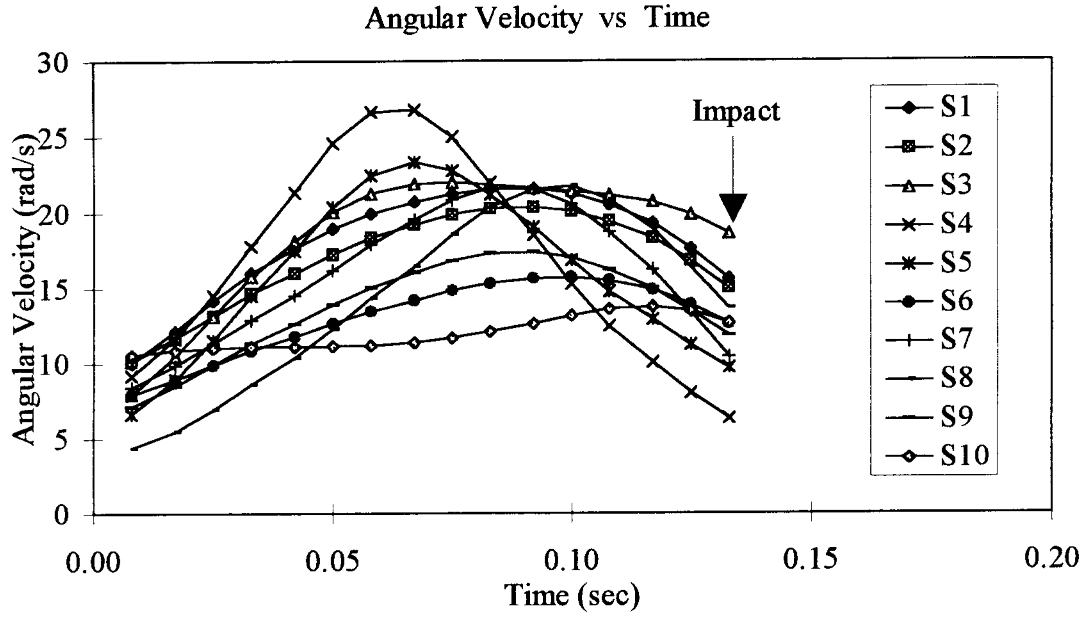

Figure 32. Angular velocity of the shank projected onto the horizontal plane at the high level kicks.

4.4.6 Angular Velocity of the Thigh Projected onto the Horizontal Plane for the Low Level, Middle Level, High Level Kicks

The angular velocities of the thigh projected onto horizontal plane for the low level, middle level, and high level kicks were observed during a period of 208 μsec prior to the impact. The angular velocity of the thigh projected onto horizontal plane for the low level kick, middle level kick, and high level kick is shown in Figure 33. The thigh reached a maximum angular velocity at 168 μsec prior to the impact for the high level kick while the maximum occurred at 136 μsec and 122 μsec prior to the impact for the middle level and low level kicks respectively. The angular velocity of the thigh for all three height level kicks reached the maximum value earlier than the shank. These results are similar to the patterns for a punt kick (Putnam, 1983) and to the pattern for Taekwondo front kicks (Park, 1989). The values of maximum angular velocity of the thigh projected onto horizontal plane for low level, middle level, and high level kicks were 15.3±2.3 rad/s, 15.8±2.7 rad/s, and 13.6±2.3 rad/s respectively. The values of the angular velocity of the shank projected onto horizontal plane at the impact for low level, middle level, and high level kicks were 4.8±1.8 rad/s, 4.4±1.2 rad/s, and 3.8±1.9 rad/s respectively. The angular velocity of the thigh projected onto the horizontal plane for the low level, middle level, and high level kicks of 10 subjects are shown in Figures 34, 35, and 36.

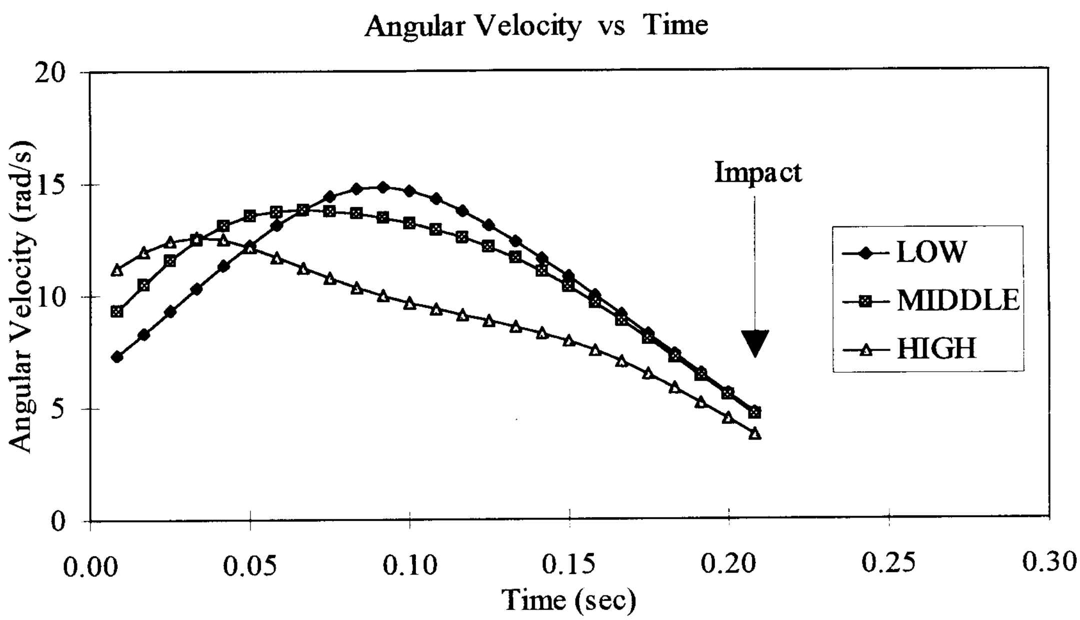

Figure 33. Angular velocity of the thigh projected onto the horizontal plane at the low level, middle level, and high level kicks.

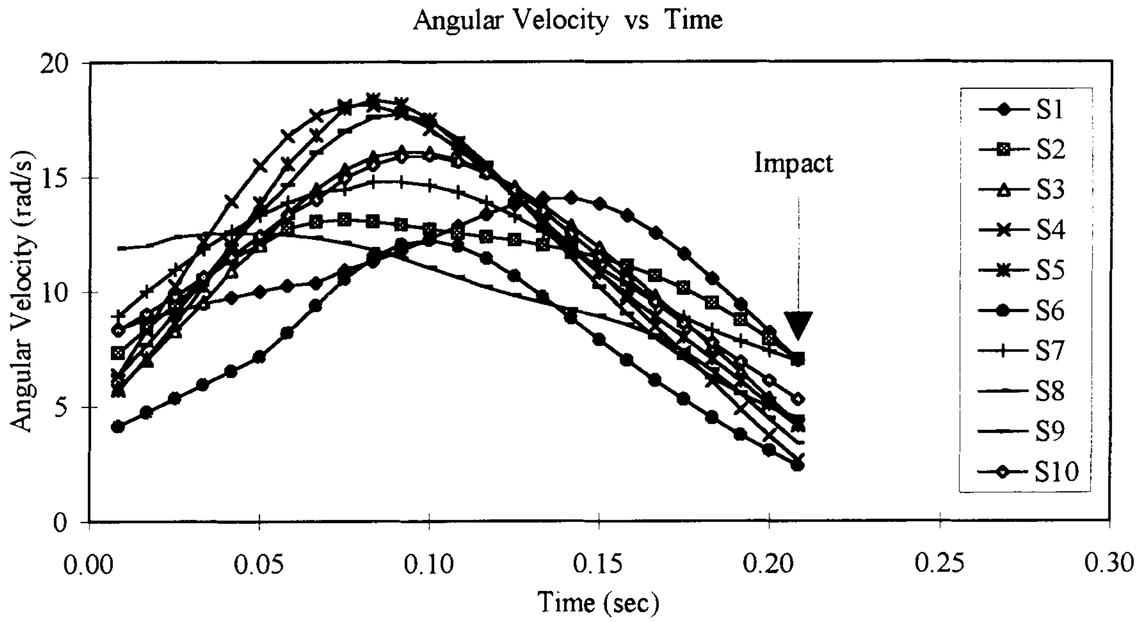

Figure 34. Angular velocity of the thigh projected onto the horizontal plane at the low level kicks.

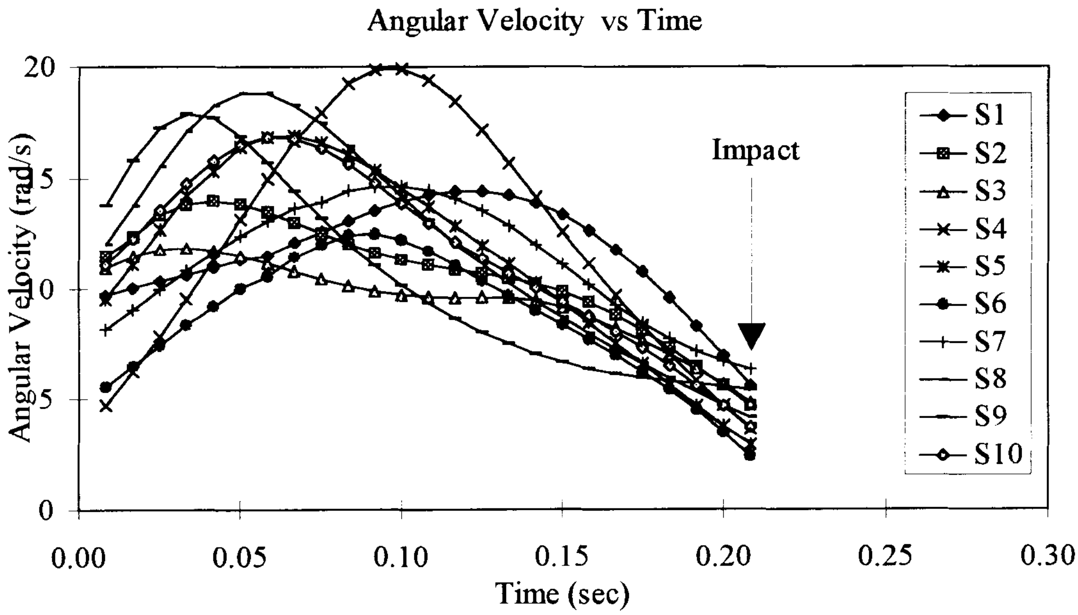

Figure 35. Angular velocity of the thigh projected onto the horizontal plane at the middle level kicks.

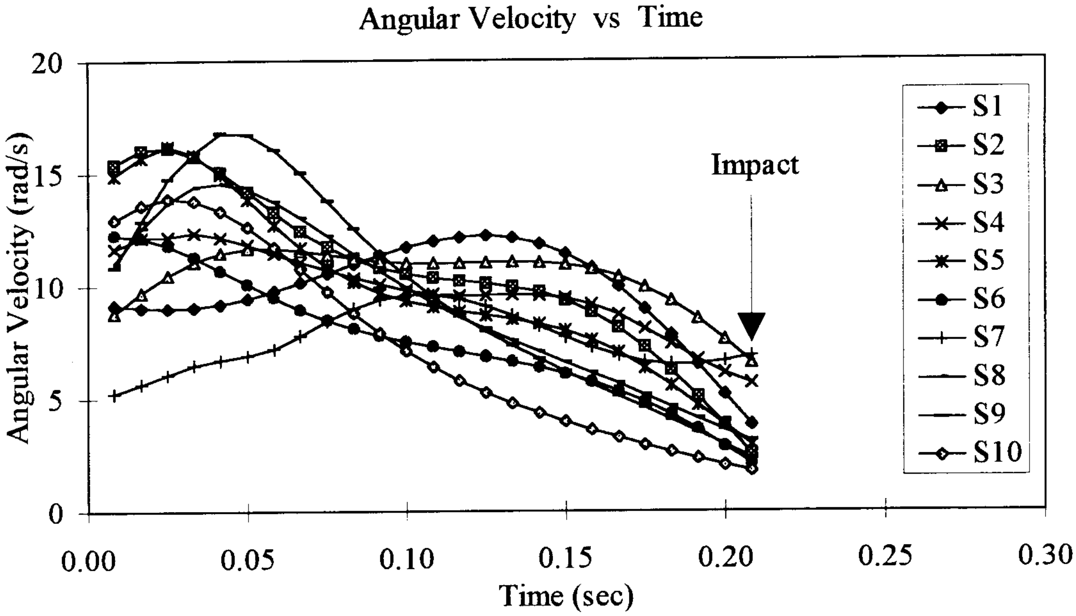

Figure 36. Angular velocity of the thigh projected onto the horizontal plane at the high level kicks.

4.4.7 Relationship between the Mean Leg Strength and the Mean Peak Force, and between the Mean Leg Strength and the Mean Impulse

Leg strength was measured by mean peak torque of knee extension, and mean peak torque of hip flexion. The correlation values between mean leg strength and mean peak force, and mean impulse are shown in Tables 7, 8, and 9. These correlations were computed from the data both including and excluding one subject (subject #6) whose leg strength could be considered as an outlier compared to the other subjects. These correlations were also computed using normalized data for leg strength, peak force, and impulse. The results showed that there was no significant correlation either between mean leg strength and mean peak force or between mean leg strength and mean impulse of the Thai Boxing Roundhouse kicks. These results did not agree with the two hypotheses that leg strength would be positively related to peak force and to impulse. These results suggests that other biomechanical factors, such as the kicking technique of the subjects, have more influence on force than the strength of the kicking leg. Another explanation may be due to the test velocities used in the measurement of the leg strength. The reasonable and comfortable range for testing angular velocities should be between 60 and 180 °/sec as recommended by Dvir (1995). For this reason leg strength in this study was measured at 120 °/sec. A potential problem is that the knee velocities actually found in the kicking trials were 500-700 °/sec so that the leg strength measures may not be as relevant as measures made at higher angular velocities.

Training experience is another factor which should affect the peak force. Subjects with more experience should have developed better kicking technique which would enable then to exert more force in kicking. This study found a significant positive relationship between the training experience and peak force ($r = .72$; $p<.05$). The subjects who had a longer period of training experience could generate greater peak force than the subjects who had shorter period of training experience in Thai Boxing.

Table 7
Correlations between leg strength and peak force, and impulse

	Peak Force VS Knee Extension	Impulse VS Knee Extension	Peak Force VS Hip Flexion	Impulse VS Hip Flexion
Including Subject #6	r = .25	r = .31	r = .11	r = .04
Excluding Subject #6	r = .23	r = .39	r = .03	r = .23

Table 8
Correlations between normalized leg strength and peak force, and impulse

	Peak Force VS Normalized	Impulse VS Normalized	Peak Force VS Normalized	Impulse VS Normalized
Including Subject #6	r = .03	r = .19	r = .11	r = .19
Excluding Subject #6	r = .08	r = .34	r = .08	r = .18

Table 9

Correlations between normalized leg strength and normalized peak force, and normalized impulse

	Normalized Peak Force VS	Normalized Impulse VS	Normalized Peak Force VS	Normalized Impulse VS
Including Subject #6	r = .18	r = .07	r = ..22	r = .34
Excluding Subject #6	r = .08	r = .30	r = .14	r = .26

4.4.8 Relationship between the Mean Final Linear Velocity of the Kicking Ankle and the Mean Peak Force, and between the Mean Final Linear Velocity of the Kicking Ankle and the Mean Impulse

There was a significant positive relationship between the mean final velocity of the ankle and the mean peak force of the Thai boxing roundhouse kick, r = .86 ($p<.05$) (Figure 37). There was also a significant positive relationship between the mean final velocity of the ankle and the mean impulse of the Thai boxing roundhouse kick, r = .79 ($p<.05$) (Figure 38). These results agreed with Hypotheses that the mean final velocity of the kicking ankle would be positively related to mean peak force and to mean impulse. The peak force results are also consistent with previous karate kick studies (Jordan, 1973, Powell, 1989). The results of the present study have shown that the mean final velocity of the ankle was a significant factor in determining the mean peak force and mean impulse at every kick height level, but that the mean final velocity is not significantly different at the different kick height levels. This suggests that Thai boxers who are able to obtain greater final velocity of the ankle will probably achieve a greater mean peak force and mean impulse at the impact of their kicks at every kick height level. This study also found that in some cases for a particular subject a higher final velocity of the kicking ankle did not result in an increase in peak force. Also, some subjects who achieved similar final velocity of the kicking ankle did not have similar results for peak force. For example, subject #1 and subject #2 both had the same mean final velocity for the high level kick (8.3 m/s), but subject #1 had a mean peak force of 12232 N compared to 9792 N for subject #2. Given the equal final velocity of the kicking ankle for these two subjects, the difference in peak force suggests that there must be a difference in the effective mass involved in their kicks. In general this factor of effective mass will be influenced by the stiffness of the kicking leg during impact. The greater the stiffness of the segments of the kicking leg at impact, the greater the effective mass and therefore the greater the amount of force (Plagenhoef, 1971).

Training experience should be another factor that affects the final velocity of the kicking ankle in Thai Boxing roundhouse kicks. Subjects with more experience should have developed better kicking technique which would enable then to achieve a greater final velocity for their kicks. This study found a significant positive relationship between the length of training time in Thai Boxing and the final velocity of the kicking ankle ($r = .78$; $p<.05$).

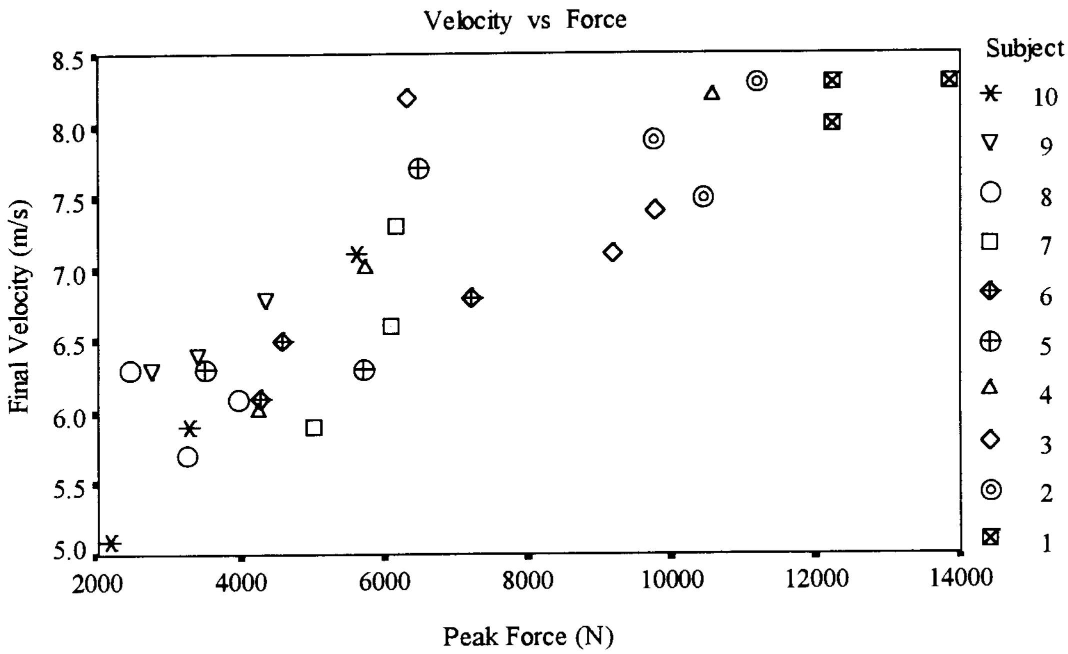

Figure 37. The relationship between the mean final linear velocity of the kicking ankle and the mean peak force of the roundhouse kick. r = .86 (p<.05).

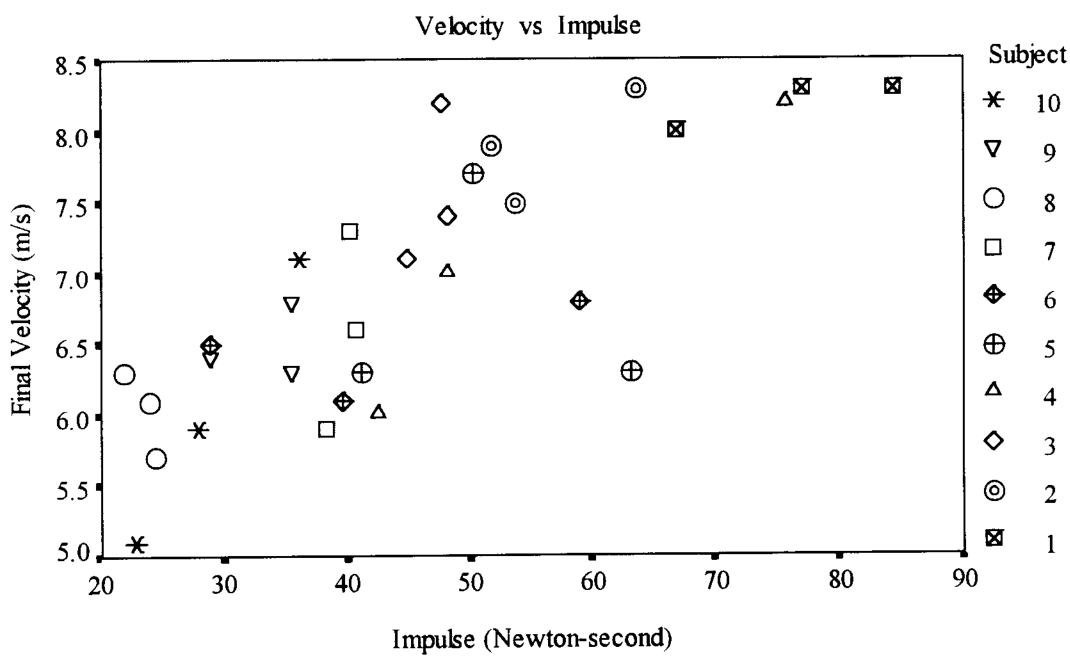

Figure 38. The relationship between the mean final linear velocity of the kicking ankle and the mean impulse of the roundhouse kick. r = .79 (p<.05).

4.5 Discussion of Methods and Results

The purpose of this study was to measure kinetic and kinematic variables for the Thai Boxing roundhouse kick. The kinetic analysis required measurements of the force generated by the roundhouse kick. A unique feature of this study was the use of a triaxial accelerometer to measure the acceleration of a known mass kicking bag in order to calculate the force of the kick which accelerated the bag. An important requirement of this methodology was to validate the force measure derived from the acceleration data. The first attempt to validate this measure used a force transducer mounted on the front of a rectangular steel plate used as a ram. This ram was suspended from the ceiling like a pendulum so that it could be swung into the kicking bag. In this way the force determined from the acceleration of the bag could be compared to the force measured by the force transducer mounted on the ram. Two problems occurred with this approach. To get an accurate measure from the force transducer the surface of the sensor must be perpendicular to the target at the point of contact. In fact, it was difficult to swing the ram so that it consistently struck the kicking bag squarely. The second problem was that the amount of force that could be generated by the ram was much less that the force generated by the roundhouse kick. Adding weight to the ram or increasing the arc of the swing can increase the amount of force. In this case it was not possible to add enough weight and still be able to control the ram so that it would strike the bag properly. Increasing the arc of the swing made the ram control problem even worse. Also because of the fixed ceiling height in the laboratory it was only possible to make limited adjustments to lengthen the pendulum to increase the arc of the swing. The second approach to validate the acceleration method of measuring force was to drop the kicking bag onto a force plate from a series of different heights. This approach was successful in simultaneously collecting the force data measured by the force plate and the force data computed from the triaxial accelerometer inside the kicking bag. This method did allow for a wide range of peak force levels to be included in the measurement comparisons. The results showed that the triaxial accelerometer did provide a reasonable measure of force compared to the force measured by the force plate.

The kinematics part of this study required the use of at least two cameras to enable a three dimensional analysis. The data collection method selected was the MacReflex motional analysis system using three cameras. This system tracks reflective markers attached to anatomical landmarks of the subjects. The primary problem encountered was that the motion of the Thai Boxing roundhouse kick involved the rotation of body segments in such a way that it was not possible for the three cameras to continuously track all of the markers. The real problem here was that the kicking bag was suspended in the center of the movement field covered by the three cameras. It was not possible to set the proper camera angles to track the markers throughout the complete kicking motion without the view of one or more cameras being obstructed by the bag. This problem resulted in the loss of some data points that restricted the final kinematic analysis. In particular, it was not possible to collect the kinematic data for the supporting leg or for the left hip. Future studies should be able to overcome this problem by adding more cameras to the MacReflex motion analysis system. For the present study additional cameras were not available.

The results of this study can be compared to previous studies involving martial arts kicks. The present study found that the range of peak force of the Thai Boxing roundhouse kick (2000 N to 14000 N) showed higher force levels than the range of peak force of the karate kick (1223 N to 9750 N) (Jordan, 1973, Powell, 1989). The values of the mean peak forces and standard deviations for low level, middle level, and high level kicks were 6702±3514 Newtons, 7420±3477 Newtons, and 5618±3253 Newtons respectively. The mean peak force results of this study were also greater than those found for karate kicks (3189 N, Jordan 1973, and 5381 N, Powell, 1989). In comparing these studies it should be noted that both of the karate studies used subjects who had first degree black belt rankings. That is, these studies used elite subjects, but this present study used subjects that would be classified as novice to intermediate Thai Boxing performers. This suggests that elite Thai Boxing performers could create even greater force differentials in comparison to karate. It was not possible to compare the peak force of the Thai Boxing roundhouse kick to Taekwondo kicks because the previous Taekwondo research has focused on ground reaction force and not kicking force. For kinematic analysis, comparisons are limited due to data collection problems previously discussed. However, the velocity of the kicking ankle at impact for Thai Boxing roundhouse kick can be compared to the final velocity of the kicking foot in karate and Taekwondo. In the present study the final velocities of the kicking ankle for the low level, middle level, and high levels were 6.9 m/s, 7.1 m/s, and 6.8 m/s respectively. These values were greater than final velocities of the kicking foot in karate (3.8 m/s to 6.5 m/s) (Jordan, 1973, Powell, 1989), but less than the final velocities of the kicking foot in Taekwondo kicks (6.9 m/s to 7.5 m/s) (Park, 1989).

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

Muay Thai, or Thai Boxing, is a unique martial art and a method of self-defense. Thai Boxing allows the use of four offensive maneuvers : punches, elbow-strikes, knee-strikes, and a variety of kicks to attack any part of the opponent's body. Among the four attacking skills of Thai Boxing, the roundhouse kick is the most dangerous weapon with which to devastate the opponent (Young, 1991). Although the roundhouse kick is a powerful weapon, protective gear is not required to be worn in Thai Boxing. Consequently many Thai boxers have received brain concussions, fractured bones and soft tissue injuries as a result of being hit by roundhouse kicks.

There has been no scientific research concerning any Thai Boxing maneuver. The purpose of this study was to measure the peak force and impulse of the Thai Boxing roundhouse kick, and to describe the motion of this type of kick. Specifically, the study determined and compared the peak force, impulse, and final velocity of the ankle at the low level, middle level, and high level kicks. In addition, kinematic variables, linear velocity of the ankle and knee, angular velocity of the knee, angular velocity of the shank and thigh projected onto the horizontal plane were determined. The study also assessed the relationship between leg strength to peak force and impulse, and determined the relationship between final velocity of the ankle and peak force, and impulse.

In order to accomplish the primary purpose of this study, a kicking bag was designed and constructed and a triaxial accelerometer was inserted into the center of the bag. Forces were determined from the acceleration curves and known mass of the bag. The MacReflex motion analysis system was utilized to obtain 3-D coordinates of the roundhouse kicks. From the position data, motion of the ankle, knee, and hip were determined. Subsequently velocity and angular velocity were calculated.

Ten male Thai Boxing performers from the local area participated in the study. These subjects had experience in Thai Boxing training ranging from 8 months to 4 years. These subjects performed three roundhouse kicks for three height levels, low, middle, and high which were scaled to each subject's leg length. A PC computer was used with a Microsoft QuickBasic program written to record kinetic data from the triaxial accelerometer while MacReflex motion analysis system with three cameras was employed to obtain the 3-D coordinates of kinematic data. It was hypothesized that peak force and impulse would decrease as kick height increased. It was also hypothesized that linear velocity of the ankle would increase as kick height increased. Other hypotheses were that leg strength would be positively related to peak force and to impulse and that the final velocity of the ankle would be positively related to peak force and to impulse.

The mean peak force exerted by the roundhouse kick at the low level and middle level kicks was significantly greater than that of the high level kick (7014, 7420, and 5618 N respectively). The mean impulse exerted by the roundhouse kick at the middle level kick was significantly greater than that of the high level kick. There was no significant difference between the mean impulses exerted by the low level and middle level kicks, or between the mean impulses exerted by the low level and high level kicks (45.3 N-s, 50.2 N-s, and 40.6 N-s, respectively). Final velocities of the ankle were similar at each height (6.9, 7.1, 6.8 m/s, respectively).

No relationship was found to exist between either leg strength and peak force or impulse for the roundhouse kick. That is, the peak force and impulse of the roundhouse kick did not appear to be affected by leg strength.

There was a positive relationship found between the mean final velocity of the ankle and the mean peak force exerted by the roundhouse kick. A positive relationship also existed between the mean final velocity of the ankle and the mean impulse exerted by the roundhouse kick.

Mean final velocity of the ankle was the major factor related to the peak force exerted by the roundhouse kick. In order to obtain higher final velocity of the kicking foot as well as kicking ankle, the movement contribution of the other parts of the body such as the pivoting of the supporting leg and hip rotation should be considered.

Many injuries occur in the sport of Thai Boxing and are often caused by the roundhouse kicks. This type of kick generates a high peak force and large impulse which are likely to be related to the severity of injuries. The peak force levels of the roundhouse kicks from this study were as large as 14000 N. More experienced boxers should be capable of even greater impact forces. In a cadaver study, Patrick, Mertz & Kroell (1993) found that facial bone fractures occurred when the amount of force of 11743 N was applied to a head target which was covered with 15/16 inches of padding. This study also found rib fractures occurred when the amount of force of 5960 Newtons was applied to the chest target covered with 15/16 inches of padding. In a primate study, Shatsky, Alter, Evans, Armbrustmacher, Earle, & Clark (1993) found that the minimum impact force for skull fractures was 2447 N and the threshold for fatal skull injury was 2562 N. They also found that some brain pathology could occur at a peak force level as low as 1045 N. The study also concluded that increasing neurological deficits were related to increasing peak force. Based on the results of the above studies, the peak force levels found in the present study suggest that the Thai Boxing roundhouse kick can easily generate enough force to cause neurological impairment, skull fractures, facial bone fractures, and rib fractures.

5.2 Conclusions

Based on the results of this study and with awareness of its limitations several conclusions can be drawn.

In comparing the roundhouse kick at different height levels the middle level kick generated the greatest peak force and impulse, and the high level kick generated the least amount of peak force and impulse. From this result it can be concluded that the mechanics of this type of kick are most efficient at the middle level of kick and least efficient at the high level kick. This is due to the body orientation during the kick and to the magnitude of final velocity of the kicking ankle that can be generated at the different height levels. These findings suggest that a competitive Thai Boxer should concentrate his kicking attack at the middle level and low height levels. This finding also has implications for regulating the safety of this sport. That is, the middle level kick should have the greatest chance of causing an injury to the person who is kicked and the high level the least chance of causing an injury. However, the prediction of potential injury in Thai Boxing is complicated by the consideration of the vulnerability of the location on human body where the kick is received. For example, although the peak force and impulse of the high level kick are less that for the low level kicks, the potential injury of a kick to the head is likely to be much greater than the potential injury of a similar kick to the thigh. This study did not attempt to measure the comparative vulnerability of the different height levels.

Another finding of this study was that the amount of peak force and impulse were directly related to the final velocity of the ankle, but they are not related to the leg strength of the Thai Boxer. This suggests that the training for Thai Boxers should concentrate on good kicking technique and possibly other biomechanical factors such as body flexibility rather than on building leg strength.

This study found that the Thai Boxing roundhouse kick generates peak force and impulse of sufficient magnitude to cause neurological impairment, skull fractures, facial bone fractures, and rib fractures. That is, the peak forces and impulse values found in this study were greater than the peak force and impulse values previously found to cause these injuries. In discussions with Thai Boxing officials these types of injuries were acknowledged, however, at the present time neither the Professional Thai Boxing Association nor any other official sport organization in Thailand keeps any official records of these injuries. This study suggests that such statistics should be kept in order to document the actual frequency of these potential injuries. This study also found that the Thai Boxing roundhouse kick had greater values for peak force and final velocity of the kicking ankle than the values previously found for karate kicks. However, in karate competition kicks to the head are not allowed. There is also some use of protective padding in certain karate competitions. This study suggests that there is a greater need for regulations protecting the competitors in Thai

Boxing. In 1995, Thai Boxing was a demonstration sport in the Southeast Asian Games held in Chiang Mai, Thailand. It is expected that this sport will become a regular sport in the next Southeast Asian Games to be held in Indonesia in 1997, and thereafter, the sport may be added to the Asian Games and eventually the Olympics. As the sport of Thai Boxing grows safety concerns will increase and data from this type of research will be needed to guide the development of safety regulations in this sport.

The final conclusion of this study concerns the methodology of using a triaxial accelerometer to measure peak force and impulse. This method was successfully used in the situation where a force plate could not be used because of the potential for injury to subjects who are kicking a fixed surface. Even with padding the flat surface of a force plate would not closely simulate the human body as a target for Thai Boxing kicks. The use of a kicking bag as a target provided a much more realistic study of the Thai Boxing roundhouse kick.

5.3 Recommendations for Future Studies

1. Future of Thai Boxing study should measure ground reaction force of both the supporting foot and the kicking foot.
2. Future studies should include movement of the supporting leg, hips, trunk, and arms.
3. Future studies should include other offensive maneuvers that are used in Thai Boxing.
4. Future studies should include elite Thai Boxers as the forces are likely to be much greater than observed with the subjects of this study.

5.4 Recommendation to Professional Thai Boxing Association

Based on the impact forces observed in this study, it is clear that the roundhouse kick in Thai Boxing is potentially injurious to competitors. Protective equipment could help reduce the risk of head and trunk injuries and should be considered by the boxing association to minimize the risk of competition.

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APPENDICES

APPENDIX A

HUMAN SUBJECTS REVIEW :

KINETIC AND KINEMATIC ANALYSIS OF THAI BOXING ROUNDHOUSE KICKS

INVESTIGATOR :
Suwat Sidthilaw and Gerald Smith, Ph.D.

SIGNIFICANCE :
Thai Boxing has become one of the most popular individual sport program in the world. According to Thai Boxing rules, four offensive maneuvers, punches, elbow-strikes, knee-strikes, and a variety of kicks are allowed to be used during a fighting match. The roundhouse kick is the most dangerous maneuver with which to devastate the opponent. There has been no scientific research concerning any Thai Boxing maneuver. The investigation of kinetic and kinematic variables of the roundhouse kicks will provide Thai Boxing promoters, coaches, and boxers with a better understanding of the mechanics of the body in performing.

METHODOLOGY :
The triaxial-accelerometer will be used to determine the acceleration of the kicking bag. The peak force and impulse will be derived from acceleration and known mass bag. Video analysis method will be used to determine kinematic variables of the kicking.

This study will involve use of a kicking bag instrumental with a triaxial accelerometer and placed at three different height levels, low, middle, and high. Each subject will perform three kicks for each condition in a random order. Subjects will be allowed to have 2 minutes warm-up for each condition, 20 seconds rest between each trial, and 2 minutes rest between each height level. The kinetic data, peak force and impulse derived from accelerations of the average three kicks for each condition will be used for analysis. The kinematic data, maximum linear velocity of the kicking foot, thigh and shank, maximum angular velocity and acceleration of ankle, knee and, hip of the kicking foot, and maximum velocity of the kicking foot will be used for analysis.

RISKS AND BENEFITS :
Participation in this study carries minimal risk. The kicks of this study will be similar to those performed in typical training for Thai Boxing. The subjects will be allowed to wear an ankle brace.

The results of this study will be beneficial to promoters, coaches, and boxers in providing a better understanding of the mechanics of kicking. This information could be used for training purposes as well as for evaluation of new rules that may be helpful for the prevention of injuries in fighting matches of Thai Boxing.

SUBJECTS :

Ten volunteer Thai Boxing performers from the local area who have trained with at least six months in Thai Boxing will be recruited for this study. Ages will probably range between 20 and 35 years, though no specific age criteria have been established. The subjects will all be males as Thai Boxing does not include female participants.

INFORMED CONSENT :

Prior to the testing, each subject will be orally informed of the purposes of the study. Each subject will be asked to read and sign the Informed Consent Form (See attached) which includes the purpose of the study, procedures, and describes the minimal risks associated with the study.

ANONYMITY OF SUBJECTS :

All subjects recruited for this study will be treated anonymously in the report of findings, computer files, and results sheets, and will be referred to by numerical identification only.

Statement of Informed Consent

Title : Kinetic and Kinematic Analysis of Thai Boxing Roundhouse Kicks

Investigators : Suwat Sidthilaw and Gerald Smith, Ph.D.

Purpose : The purpose of this research is to study the roundhouse kick in Thai Boxing in order to learn about the movement of the kicking foot, ankle, knee, hip, shank and thigh. This study will determine other characteristics of the roundhouse kick relating to the speed and impact of the kick.

Procedure : I affirm that I am healthy and have no injuries of the right leg which includes ankle, knee, thigh, and hip. I have received an oral and a written explanation of this study and I understand that as a participant in this study the following things will happen :

1. All participants in this study will be right footed Thai Boxing performers with at least 6 months training in Thai Boxing.

2. All testing will be conducted in the Biomechanics and Sport Medicine Laboratories in the Women's Building at Oregon State University. As a subject, I will report to the laboratories on time, dressed in shorts, and wear an ankle brace, for the following procedures :

    a. Anthropometric measurements : My body measurements will be taken for Weight, Height, Leg Length, and Leg Strength. Removable markers will be placed on my anatomical landmarks, specifically my left ankle, right ankle, right knee, and right hip.

    b. Warm-up: I will be given at least 5 minutes for initial warm-up and at least 2 minutes to warm-up and to practice kicking for each height level of kicking.

    c. Data Collection : When I am ready I will perform three trials of roundhouse kicking at a target kicking bag at each of 3 target heights representing the level of the thigh, lower rib, and head. I will have 30 seconds to rest between each trial and 2 minutes to rest between each height level. I may quit at any time if I feel uncomfortable or overly fatigued.

I understand that the risks associated with this study are minimal. In order to prevent ankle injury and/or skin irritation of the instep of the kicking foot, I will wear an ankle brace. For the many trials in this study there may develop some fatigue and instep soreness.

My identity will be kept confidential and the records of performance will refer to me by numerical code only.

The results of this study will be beneficial to promoters, coaches, and Thai boxers in providing a better understanding of the mechanics of kicking. This information could be used for training purposes as well as for evaluation of new rules that may be helpful for the prevention of injuries in fighting matches of Thai Boxing.

I understand that my participation in this study will be approximately 30 minutes in the laboratory.

I have been completely informed about and understand the nature and purpose of this study. The researcher has offered to answer any further questions that I may have. I understand that my participation in this study is completely voluntary and that I may withdraw from the study at any time without prejudice or loss of benefits to which my participation may entitle me.

I understand that any questions I have about the research study and/or specific procedures should be directed to Suwat Sidthilaw at (503) 737-5933 or Gerald Smith at (503) 737-5928. Any other questions that I have should be directed to Mary Nunn, Sponsored Programs officer, OSU Research Office, (503) 737-0670.

My signature below indicates that I have read and that I understand the procedures described above and give my informed and voluntary consent to participate in this study. I understand that I will receive a signed copy of this consent form.

____________________________ _______________

Subject's Signature(or subject's legally authorized representative) Date

____

Subject's Name (print or type)

____________________________ _______________

Phone

____

____

Subject's Address

____________________________ _______________

Investigator's Signature Date

INSTITUTIONAL REVIEW BOARD FOR THE PROTECTION OF HUMAN SUBJECTS

OREGON STATE UNIVERSITY

Report of Review

The following project has been reviewed under the guidelines of Oregon State University's Committee for the Protection of Human Subjects and the U.S. Department of Health and Human Services:

TITLE: Kinetic and kinematic analysis of Thai boxing roundhouse kicks

PRINCIPAL INVESTIGATOR: Gerald Smith

DEPARTMENT: ExSS

STUDENT: Suwat Sidthilaw

COMMITTEE DECISION: Approved

COMMENTS:

1. The informed consent form obtained from each subject should be retained in program/project's files for three years beyond the end date of the project.

2. Any proposed change to the protocol or informed consent form that is not included in the approved application must be submitted to the IRB for review and must be approved by the committee before it can be implemented.

Redacted for privacy

Date: July 25, 1995

Warren N. Suzuki, Chair
Committee for the Protection of Human Subjects
(Education, 7-6393, suzukiw@ccmail.orst.edu)

APPENDIX B

Peak forces measured by the force plate and the accelerometers

Table 10
Peak forces measured by the force plate and the accelerometers

Trial	Force Plate : Force (N)	Accelerometers : Force (N)
1	9017	8642
2	7765	7542
3	6229	5868
4	9704	9451
5	13469	13041
6	6425	5882
7	14151	13713
8	6903	6786
9	10979	10625
10	9319	8891
11	9524	9231
12	2355	2101
13	2467	2215
14	2616	2276
15	1827	1486
16	3146	2862
17	4930	4651
18	12376	11933

APPENDIX C

Individual subjects' peak forces at three different height levels

Table 11
Peak forces of the roundhouse kick at low, middle, and high level kicks

Subject	Trial	Low	Middle	High
1	1	13059	13422	11927
	2	11404	14286	11892
	3	14524	14363	12878
	Mean	12996	14023	12232
	S.D.	1559	522	559
2	1	9078	11134	10147
	2	14076	8669	6984
	3	11837	9500	12246
	Mean	11663	9767	9792
	S.D.	2503	1254	2648
3	1	9025	11126	9222
	2	10585	9199	6263
	3	9752	9550	6310
	Mean	9787	9958	7265
	S.D.	780	1026	1694
4	1	5275	12880	4212
	2	5725	10582	4240
	3	5567	7556	3556
	Mean	5522	10339	4002
	S.D.	228	2670	387
5	1	5698	7947	3494
	2	5749	5670	3526
	3	5656	5785	4503
	Mean	5701	6467	3841
	S.D.	46	1282	573

Table 11 (continued)

Subject	Trial	Low	Middle	High
6	1	4920	8133	4266
	2	4211	6313	6515
	3	4070	5781	4551
	Mean	4400	6742	5111
	S.D.	455	1233	1225
7	1	4197	6373	4588
	2	6867	3598	5620
	3	3977	5803	6719
	Mean	5013	5258	5642
	S.D.	1608	1465	1065
8	1	2398	6197	3340
	2	2846	4013	3241
	3	2510	4005	3853
	Mean	2584	4738	3478
	S.D.	233	1263	328
9	1	4338	3922	2864
	2	3486	3147	2984
	3	3447	3124	2405
	Mean	3757	3397	2751
	S.D.	503	454	305
10	1	4790	3673	1871
	2	4779	3559	1503
	3	7220	3278	2841
	Mean	5596	3503	2071
	S.D.	1406	203	691

APPENDIX D

Individual subjects' mean peak forces at three different height levels

Table 12
Individual mean peak force of the roundhouse kicks at low, middle, and high level kicks

Subject	Low Level Kick Peak Force (N)	Middle Level Kick Peak Force (N)	High Level Kick Peak Force (N)	Mean Peak Force (N)	S.D.
1	12997	14024	12232	13084	899
2	11664	9768	9792	10408	1088
3	9787	9959	7264	9003	1509
4	8642	10339	4003	7661	3280
5	5701	6467	3841	5336	1350
6	4400	6742	5111	5418	1201
7	5014	5258	5643	5305	315
8	2585	4739	3478	3601	1082
9	3757	3411	2751	3306	511
10	5596	3503	2072	3723	1772
Mean	7014	7421	5619	6685	
S.D.	3536	3476	3254	3269	

APPENDIX E

Individual subjects' impulses at three different height levels

Table 13
Impulses of the roundhouse kick at low, middle, and high level kicks

Subject	Trial	Low	Middle	High
1	1	71	83	76
	2	63	86	76
	3	75	83	80
	Mean	70	84	77
	S.D.	6	2	2
2	1	49	61	60
	2	80	49	45
	3	58	54	66
	Mean	62	55	57
	S.D.	15	6	10
3	1	46	54	48
	2	50	45	35
	3	49	49	39
	Mean	48	49	40
	S.D.	2	5	7
4	1	38	84	46
	2	48	76	42
	3	44	58	37
	Mean	43	73	41
	S.D.	5	13	6
5	1	41	63	36
	2	60	60	35
	3	48	70	42
	Mean	50	64	37
	S.D.	10	5	4

Table 13 (continued)

Subject	Trial	Low	Middle	High
6	1	30	57	39
	2	28	61	46
	3	29	42	37
	Mean	29	53	40
	S.D.	1	10	8
7	1	35	46	35
	2	47	36	34
	3	33	36	46
	Mean	38	39	38
	S.D.	8	6	7
8	1	22	29	23
	2	23	23	24
	3	22	25	29
	Mean	22	26	25
	S.D.	1	3	3
9	1	36	35	24
	2	31	28	25
	3	26	24	22
	Mean	31	29	23
	S.D.	5	6	2
10	1	34	32	19
	2	31	31	18
	3	43	28	28
	Mean	36	30	21
	S.D.			

APPENDIX F

Individual subjects' mean impulses of at three different height levels

Table 14
Individual mean impulse of the roundhouse kicks at low, middle, and high level kicks

Subject	Low Level Kick Impulse (Ns)	Middle Level Kick Impulse (Ns)	High Level Kick Impulse (Ns)	Mean Impulse (Ns)	S.D.
1	69.4	83.8	77.0	76.7	7.2
2	62.5	54.7	57.6	58.3	3.9
3	48.2	49.1	41.0	46.1	4.4
4	60.0	72.3	42.0	58.1	15.2
5	53.2	64.5	37.8	51.8	13.4
6	28.9	53.3	40.8	41.0	12.2
7	38.4	39.3	38.7	38.8	.5
8	22.2	25.7	25.7	24.5	2.0
9	30.9	28.9	24.6	28.1	3.2
10	36.0	30.4	21.4	29.3	7.3
Mean	45.0	50.2	40.7	45.3	
S.D.	16.0	19.5	16.6	15.5	

APPENDIX G

Individual subjects' mean final linear velocities of the kicking ankle at three different height levels

Table 15
Individual mean final linear velocity of the kicking ankle of the roundhouse kicks at low, middle, and high level kicks

Subject	Low Level Kick Final Velocity (m/s)	Middle Level Kick Final Velocity (m/s)	High Level Kick Final Velocity (m/s)	Mean Final Velocity (m/s)	S.D.
1	8.0	8.3	8.3	8.2	0.2
2	7.5	7.9	8.3	7.9	0.4
3	7.4	7.1	8.2	7.6	0.6
4	7.0	8.2	6.0	7.1	1.1
5	6.3	7.7	6.3	6.8	0.8
6	6.5	6.8	6.1	6.5	0.4
7	5.9	6.6	7.3	6.6	0.7
8	6.3	6.1	5.7	6.0	0.3
9	6.8	6.4	6.3	6.5	0.3
10	7.1	5.9	5.1	6.0	1.0
Mean	6.9	7.1	6.8	6.9	
S.D.	0.6	0.9	1.2	0.8	

APPENDIX H

Individual subjects' linear velocity of the kicking ankle at three different height levels

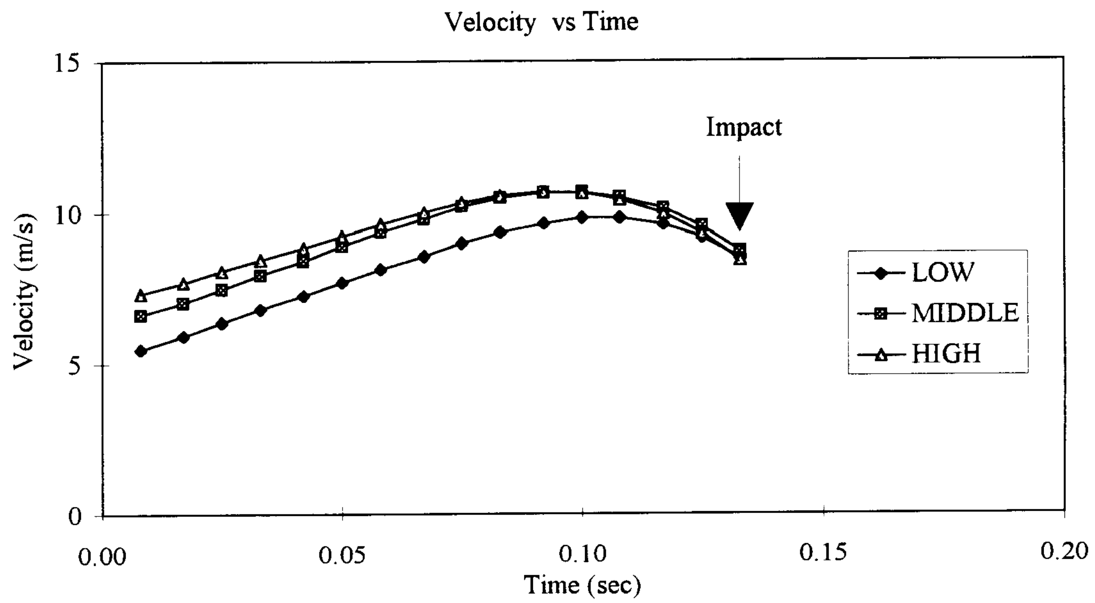

Figure 39. Linear velocity of the kicking ankle at three height levels for Subject 1.

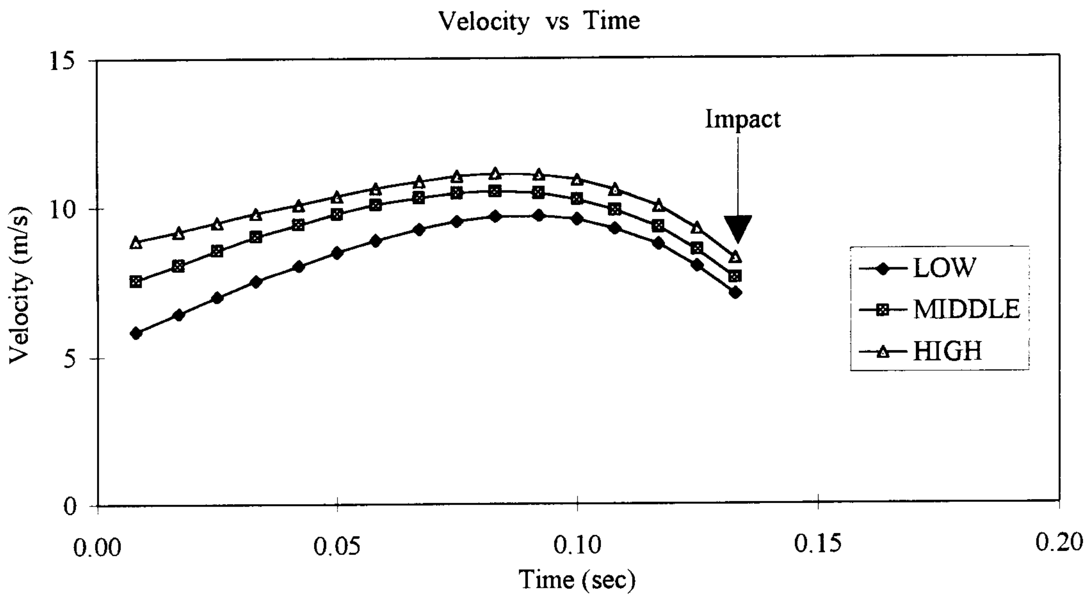

Figure 40. Linear velocity of the kicking ankle at three height levels for Subject 2.

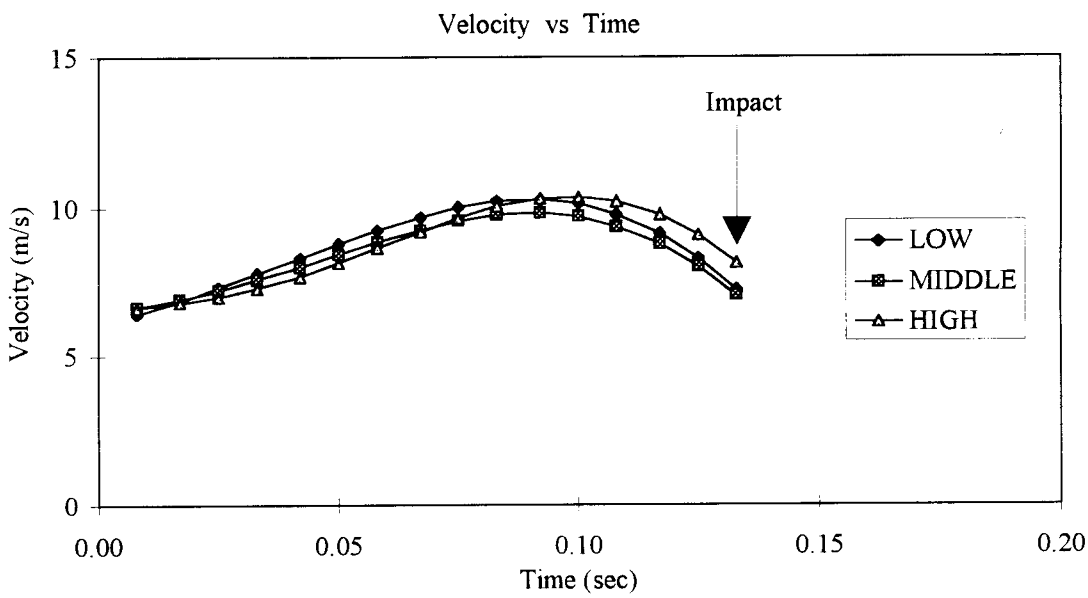

Figure 41. Linear velocity of the kicking ankle at three height levels for Subject 3.

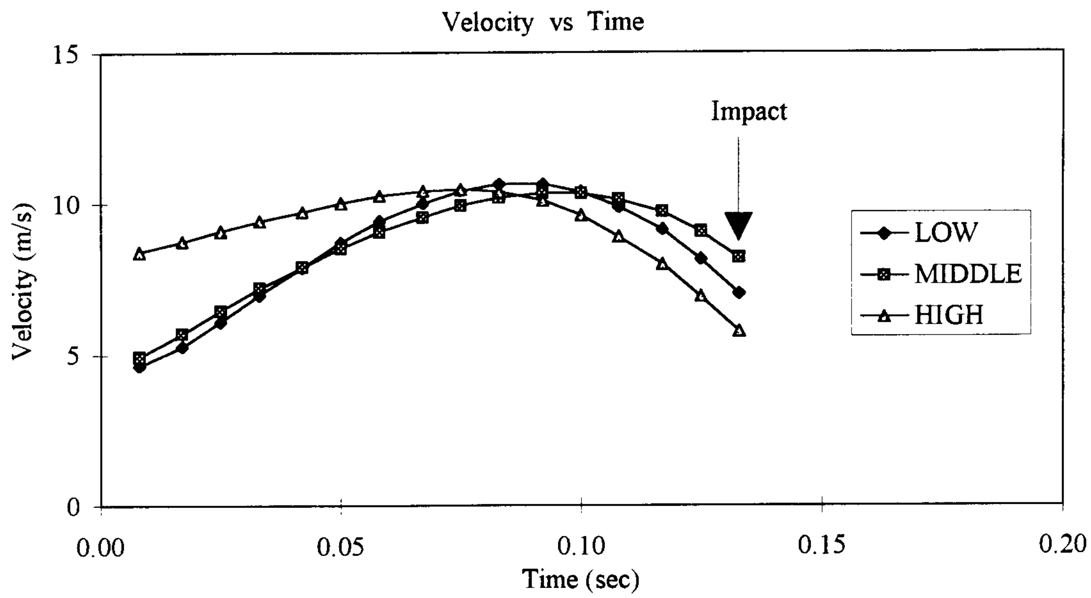

Figure 42. Linear velocity of the kicking ankle at three height levels for Subject 4.

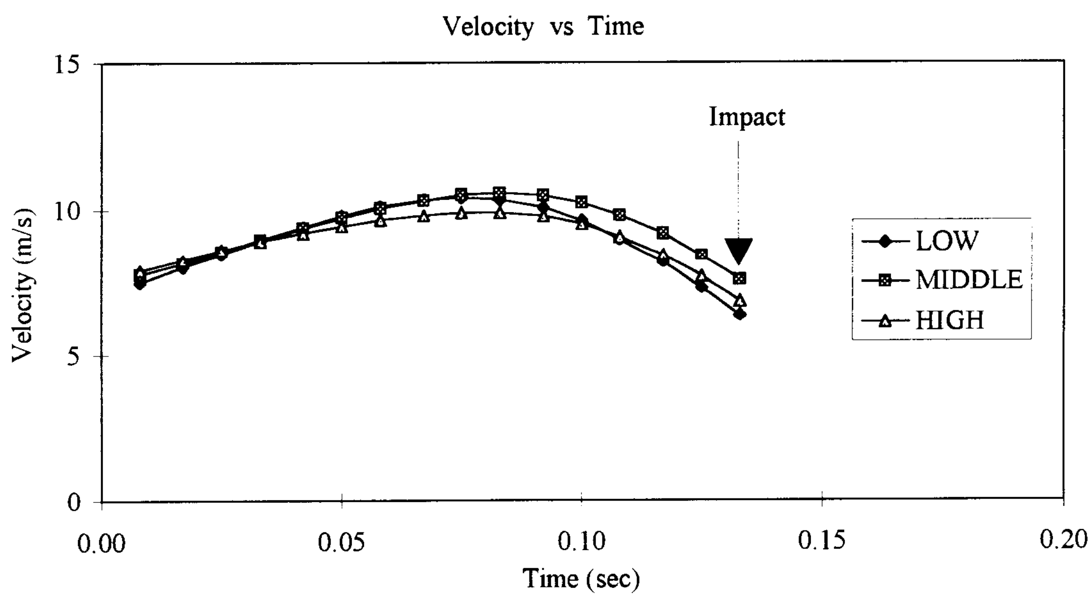

Figure 43. Linear velocity of the kicking ankle at three height levels for Subject 5.

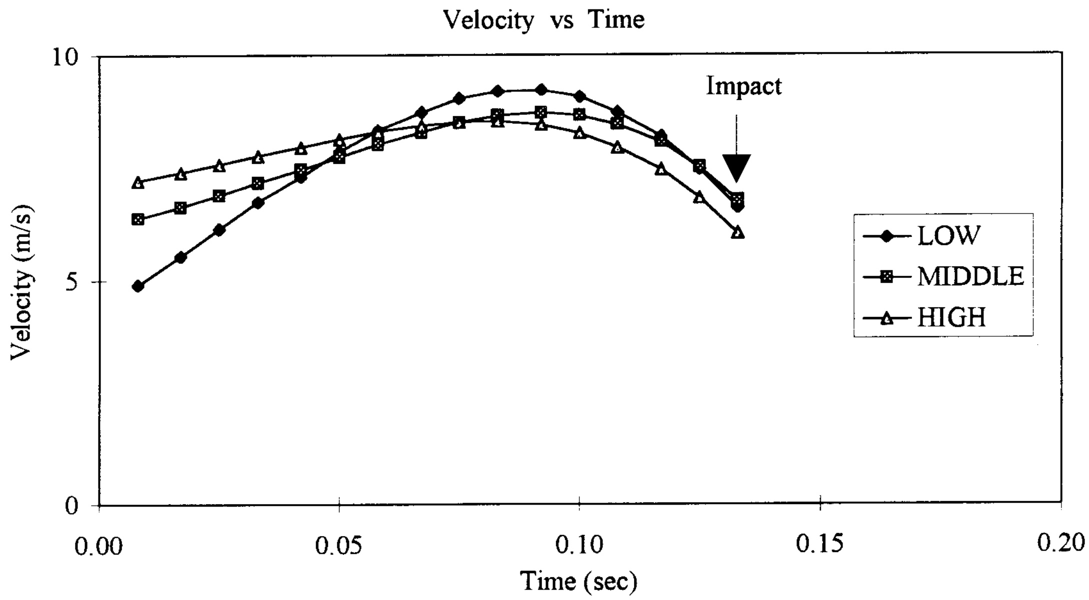

Figure 44. Linear velocity of the kicking ankle at three height levels for Subject 6.

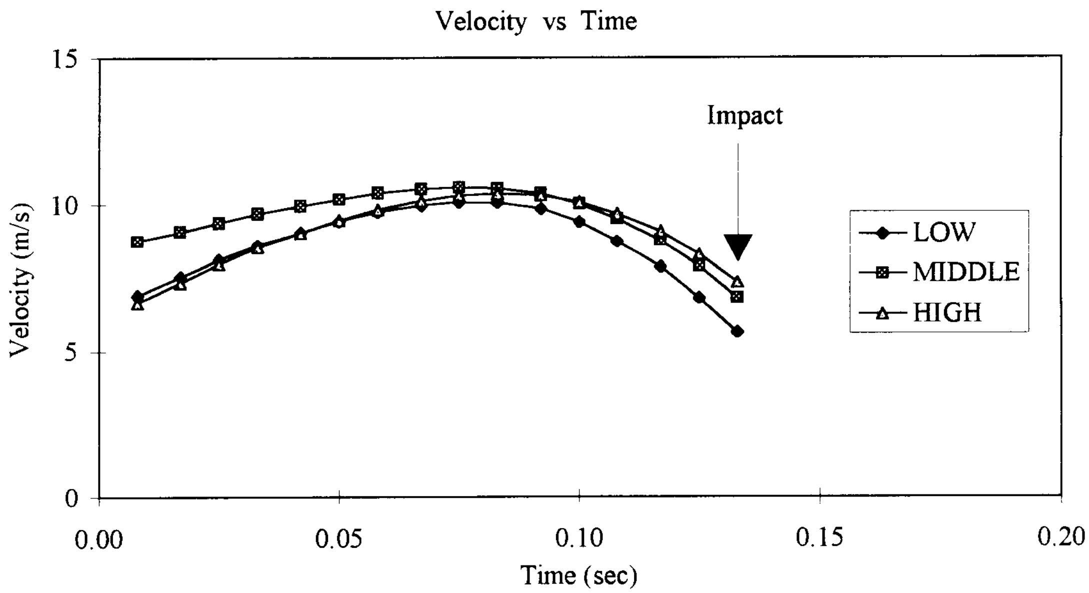

Figure 45. Linear velocity of the kicking ankle at three height levels for Subject 7.

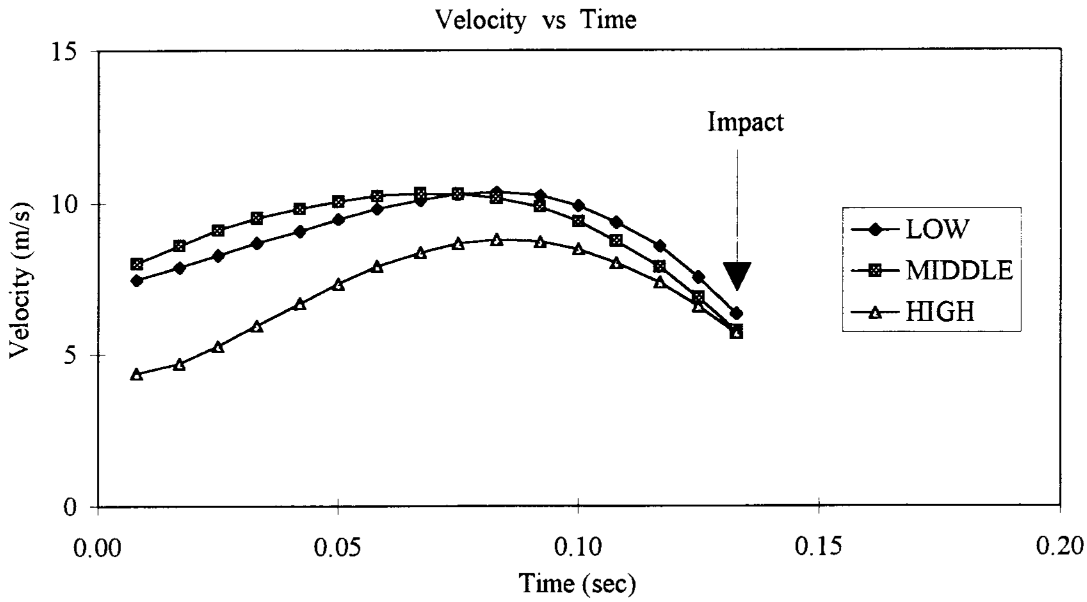

Figure 46. Linear velocity of the kicking ankle at three height levels for Subject 8.

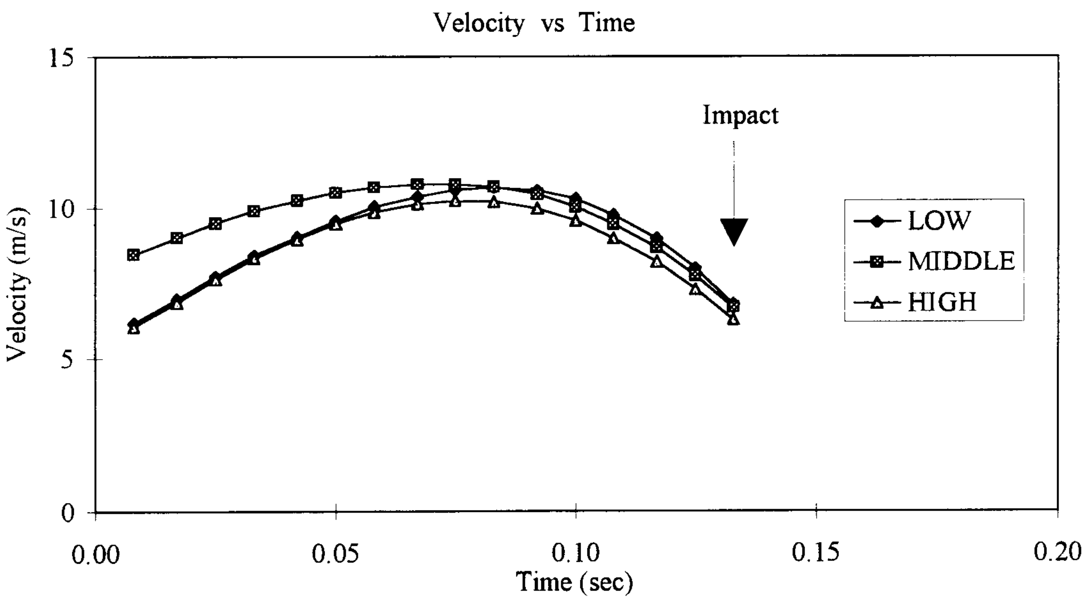

Figure 47. Linear velocity of the kicking ankle at three height levels for Subject 9.

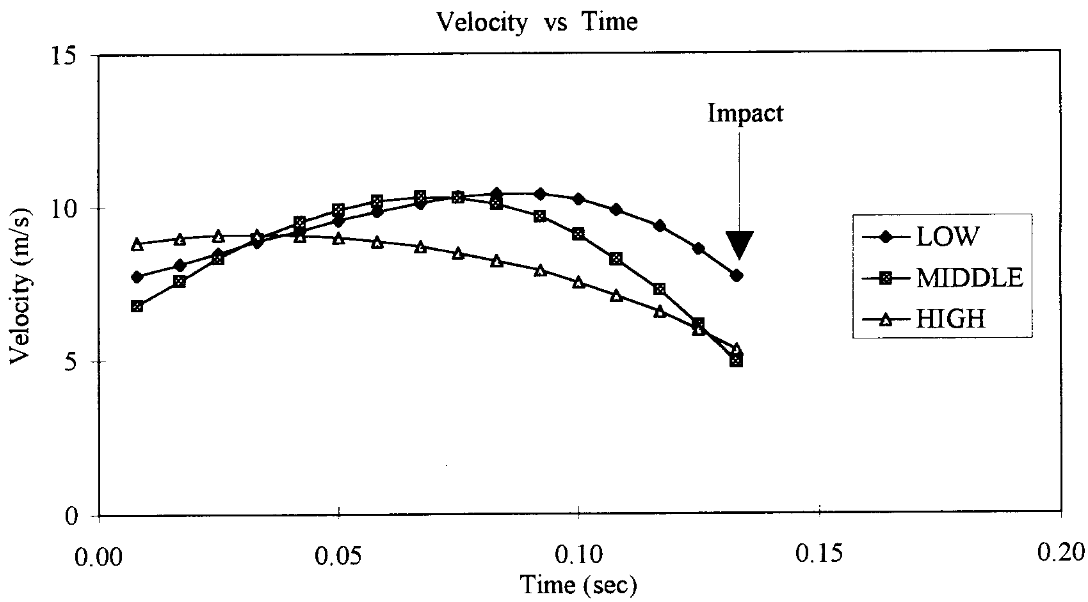

Figure 48. Linear velocity of the kicking ankle at three height levels for Subject 10.

APPENDIX I

Individual subjects' linear velocity of the knee at three different height levels

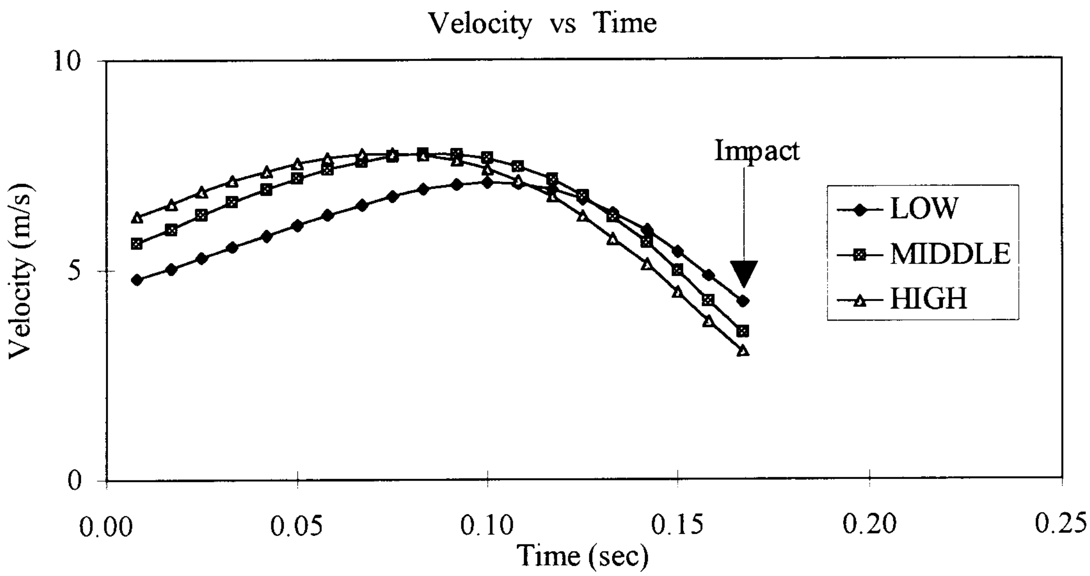

Figure 49. Linear velocity of the knee at three height levels for Subject 1.

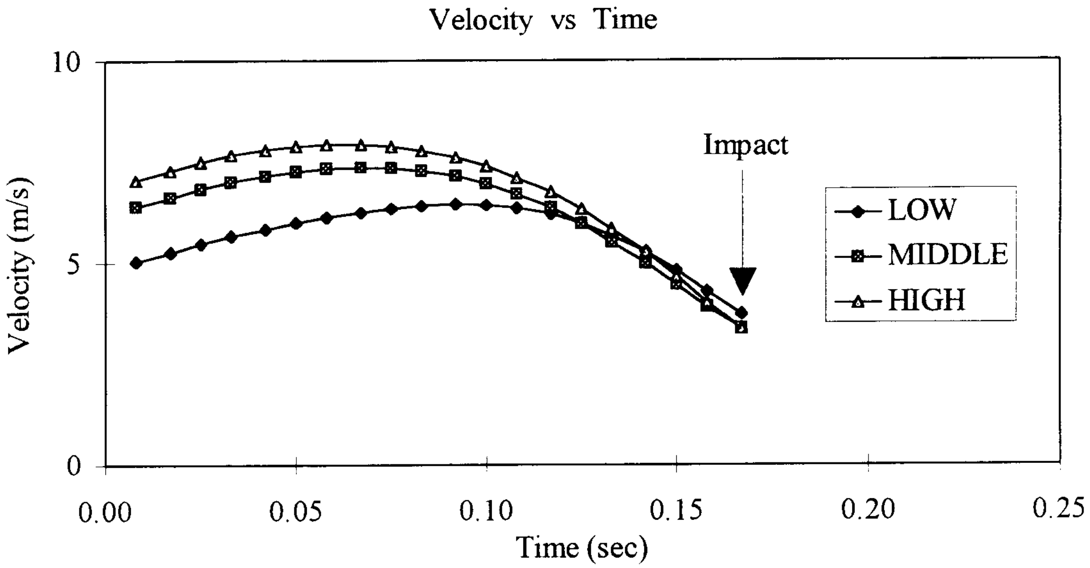

Figure 50. Linear velocity of the knee at three height levels for Subject 2.

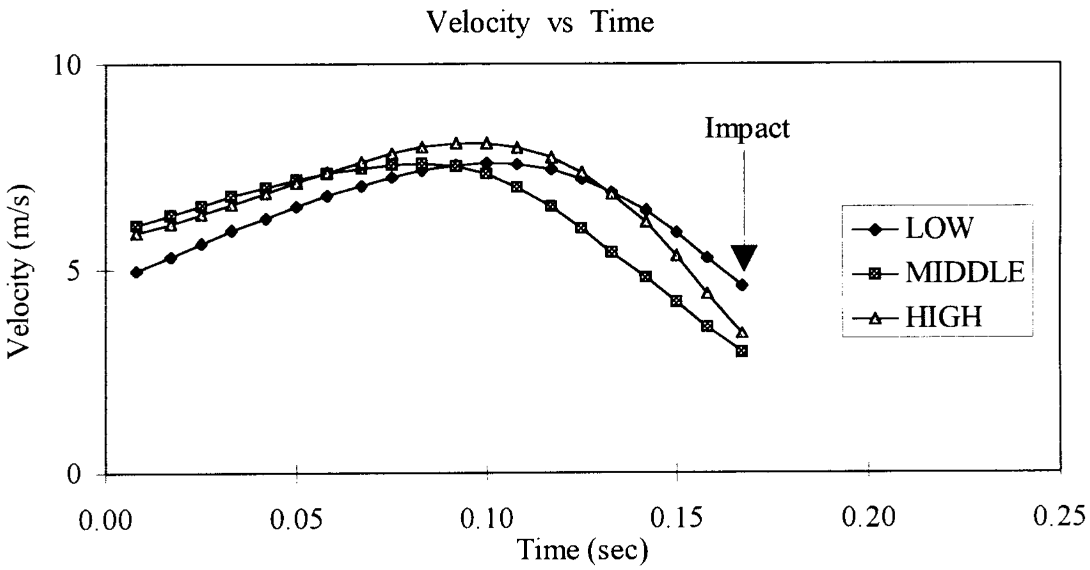

Figure 51. Linear velocity of the knee at three height levels for Subject 3.

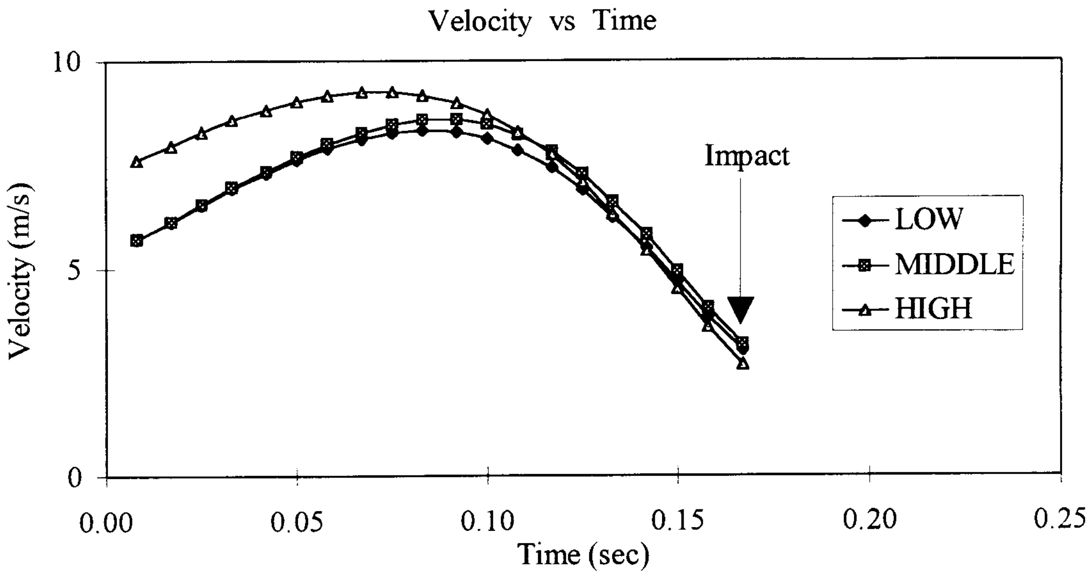

Figure 52. Linear velocity of the knee at three height levels for Subject 4.

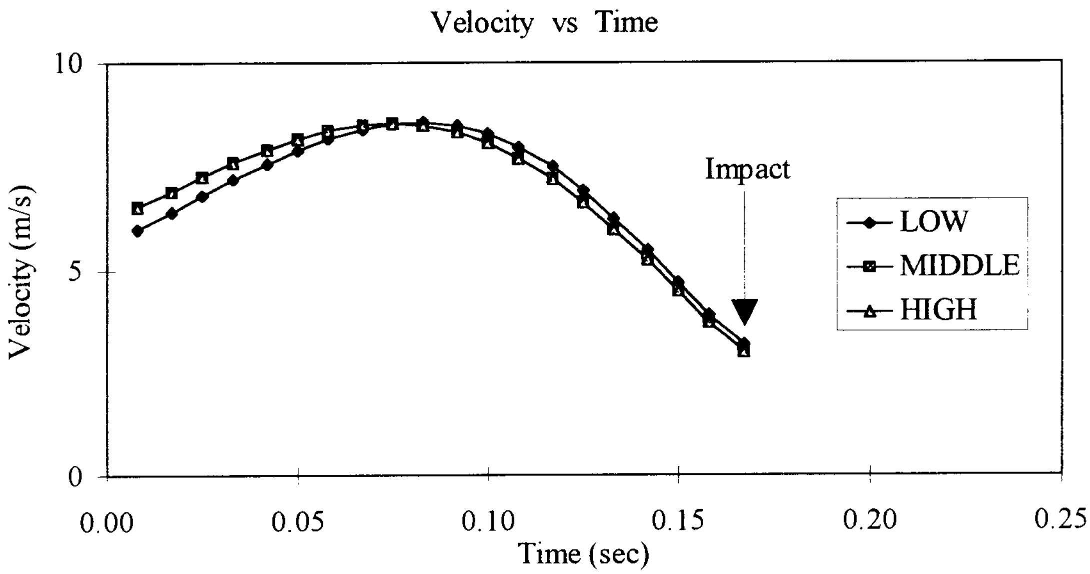

Figure 53. Linear velocity of the knee at three height levels for Subject 5.

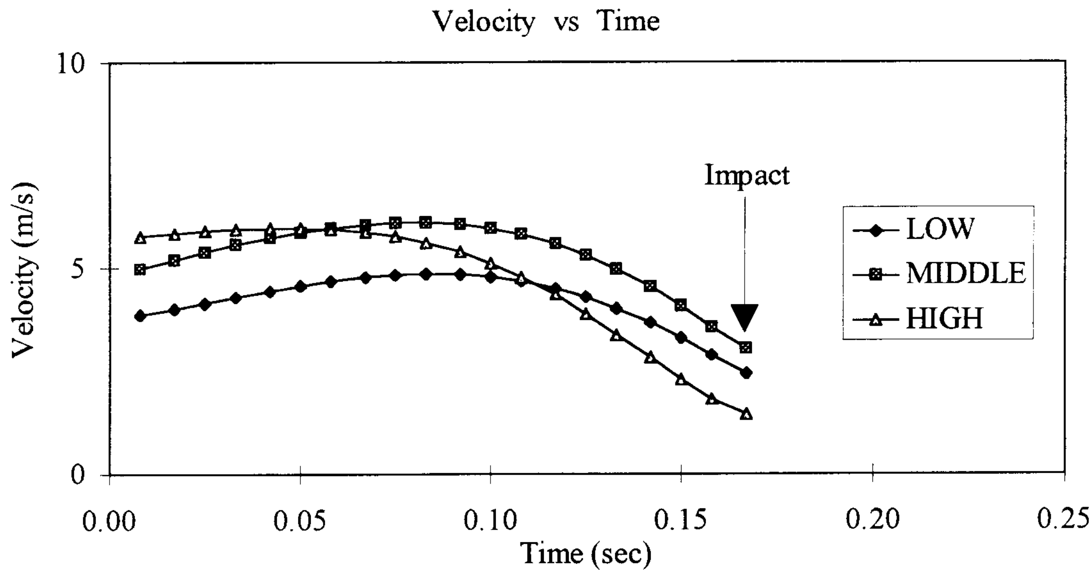

Figure 54. Linear velocity of the knee at three height levels for Subject 6.

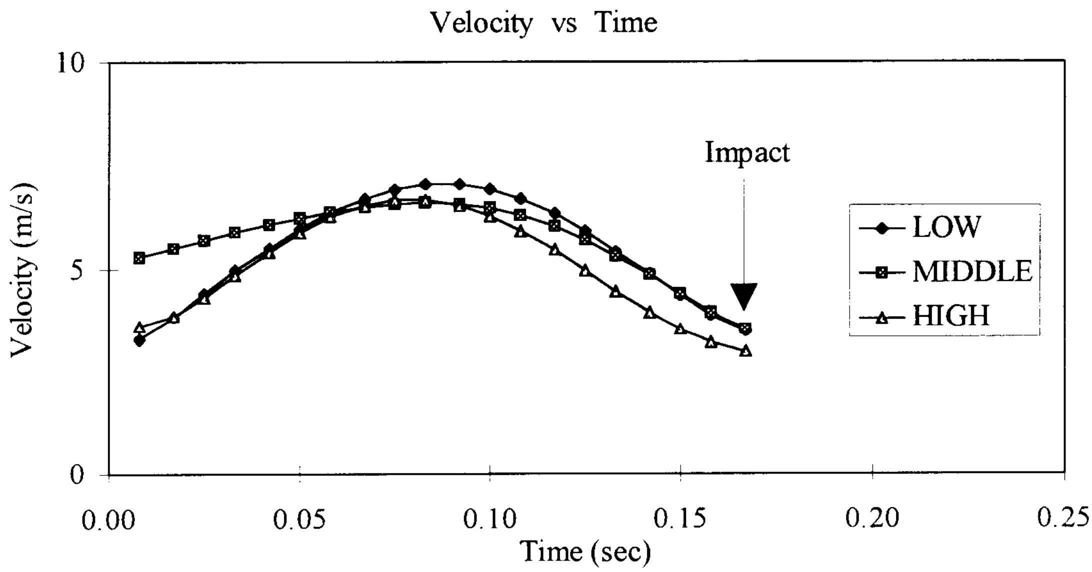

Figure 55. Linear velocity of the knee at three height levels for Subject 7.

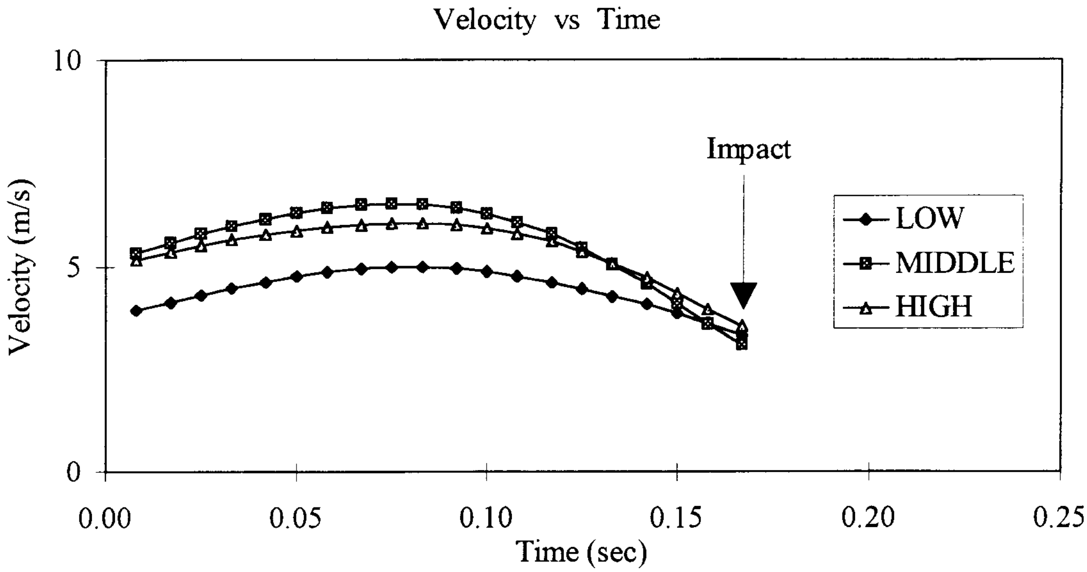

Figure 56. Linear velocity of the knee at three height levels for Subject 8.

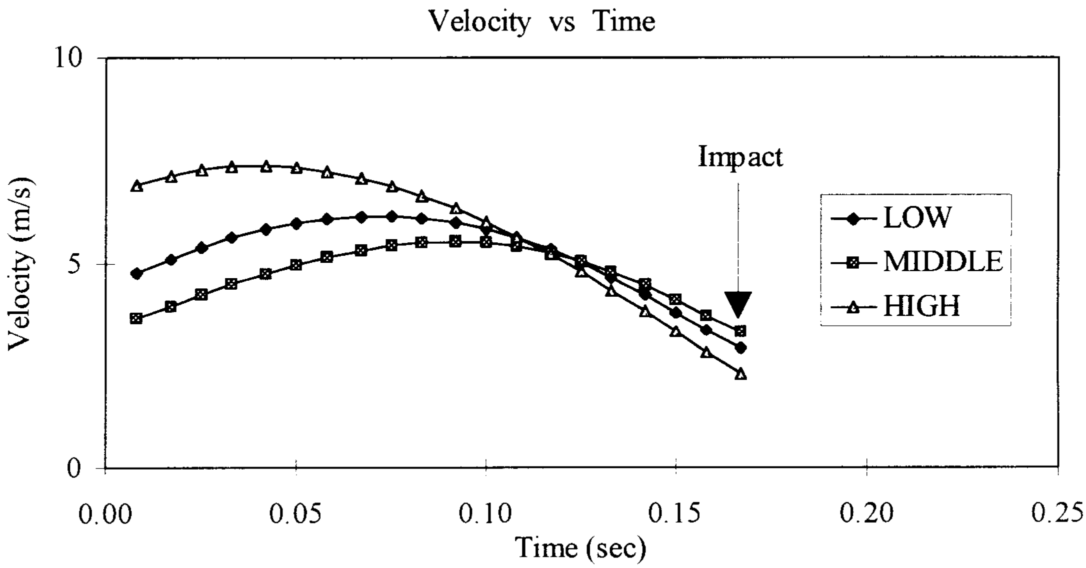

Figure 57. Linear velocity of the knee at three height levels for Subject 9.

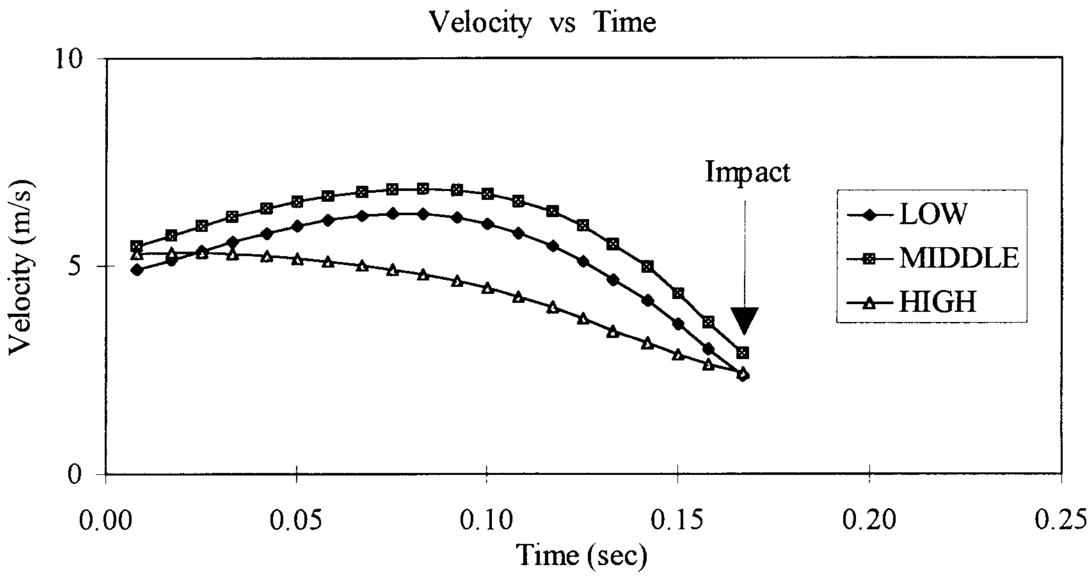

Figure 58. Linear velocity of the knee at three height levels for Subject 10.

APPENDIX J

Individual subjects' angular velocity of the knee at three different height levels

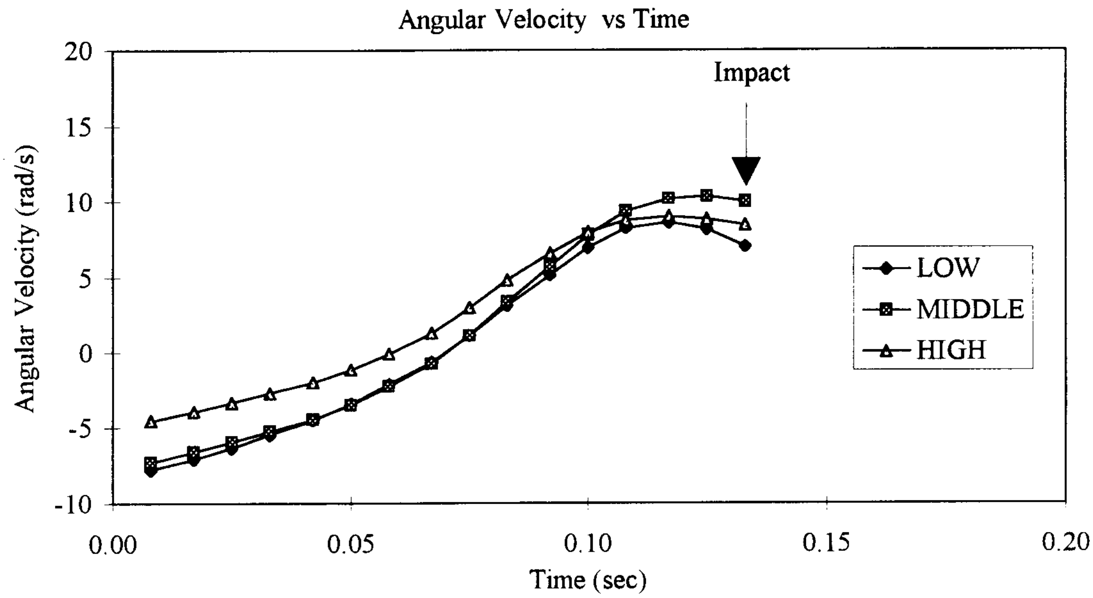

Figure 59. Angular velocity of the knee at three height levels for Subject 1.

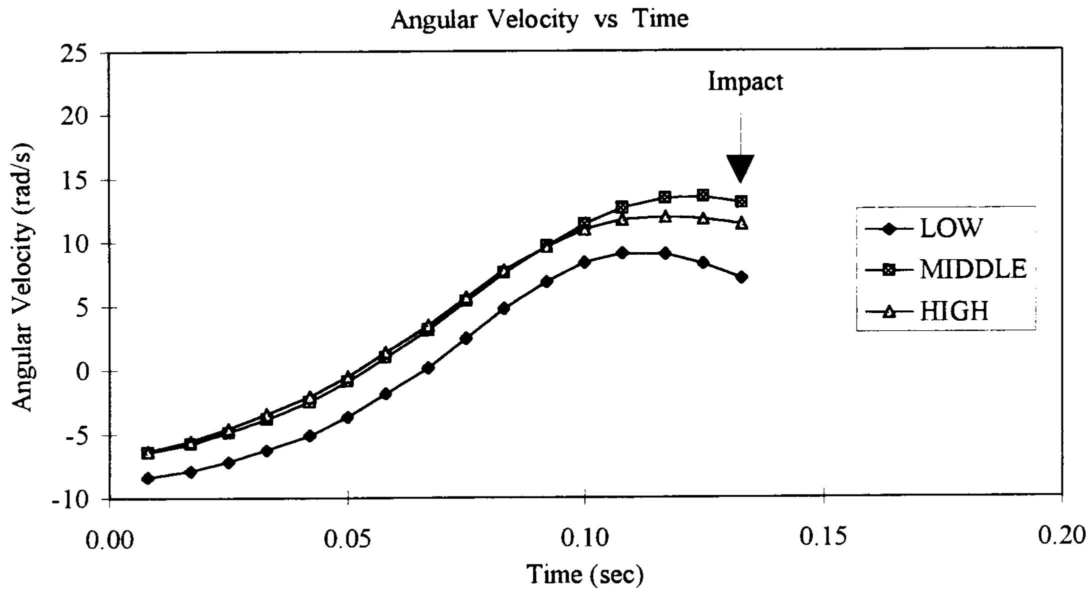

Figure 60. Angular velocity of the knee at three height levels for Subject 2.

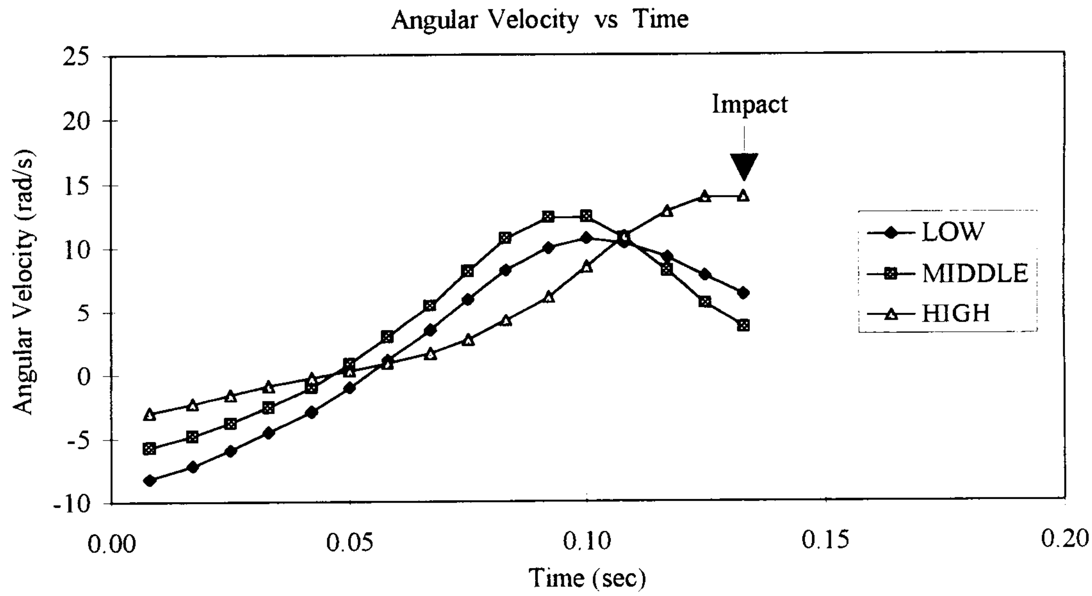

Figure 61. Angular velocity of the knee at three height levels for Subject 3.

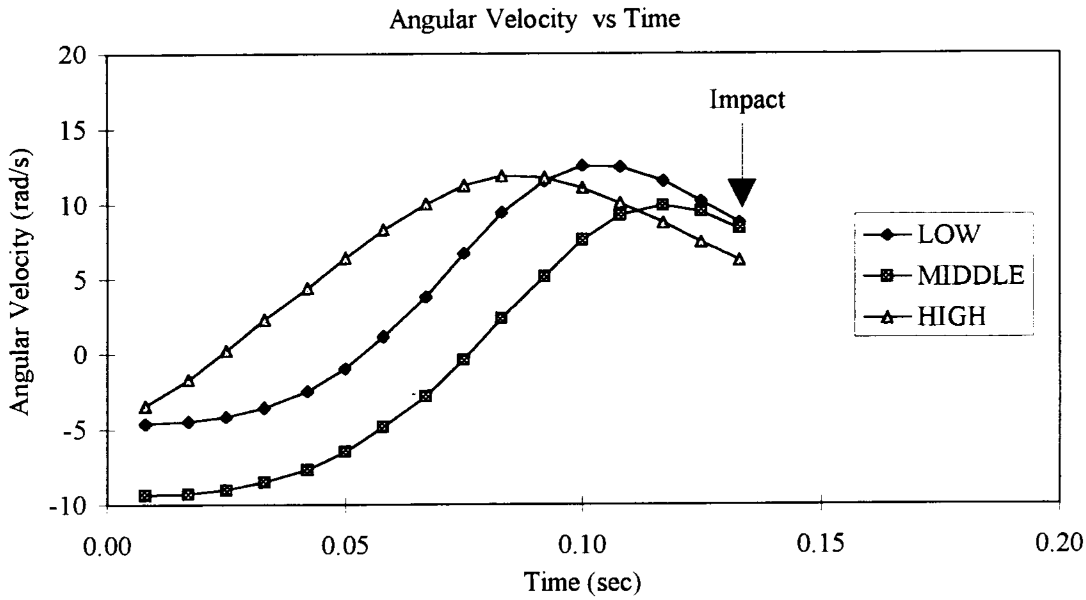

Figure 62. Angular velocity of the knee at three height levels for Subject 4.

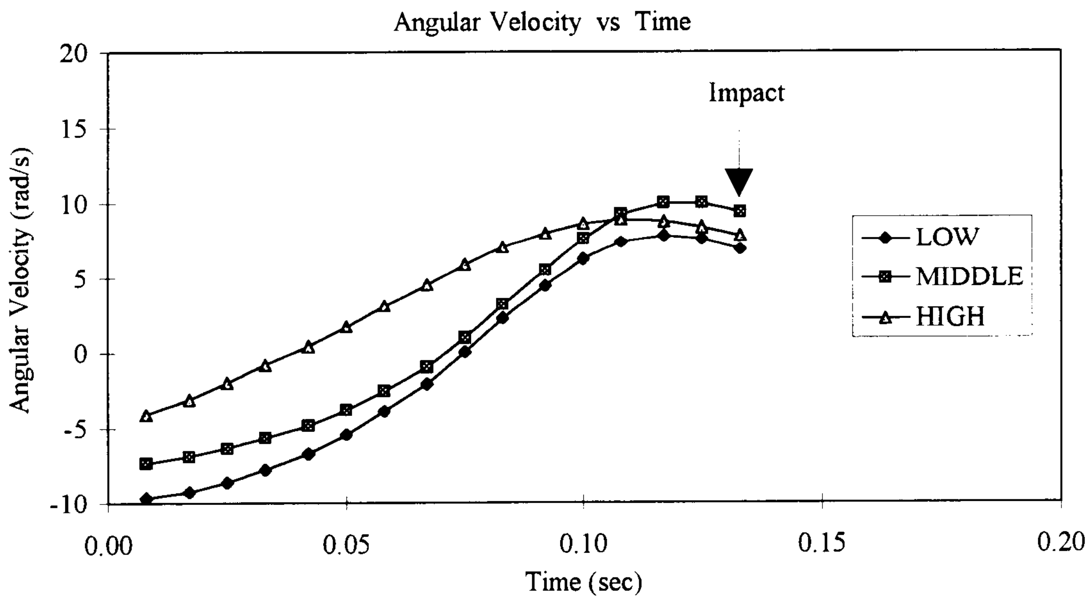

Figure 63. Angular velocity of the knee at three height levels for Subject 5.

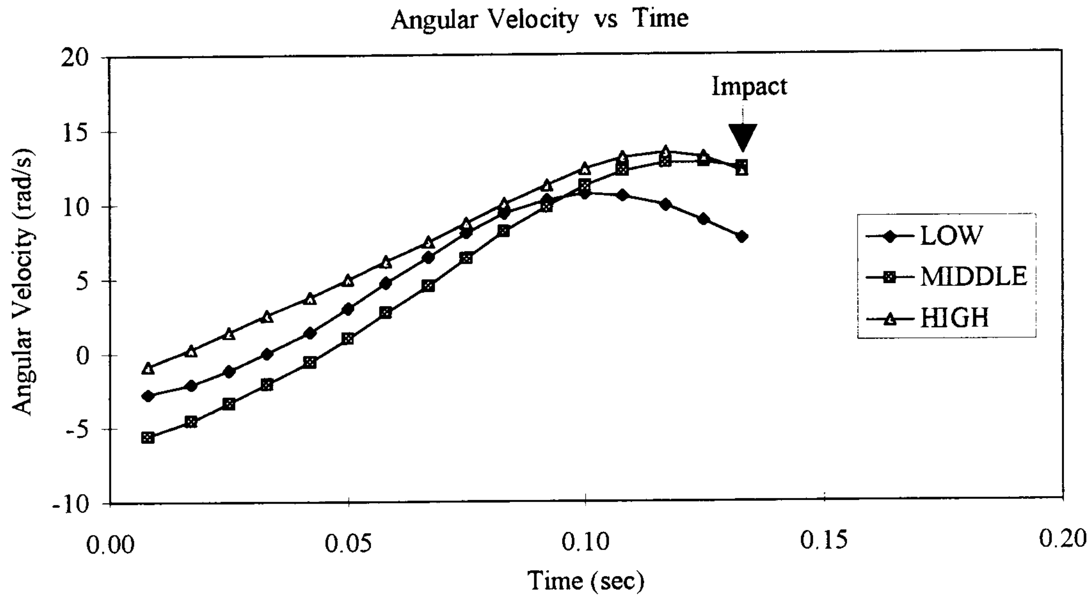

Figure 64. Angular velocity of the knee at three height levels for Subject 6.

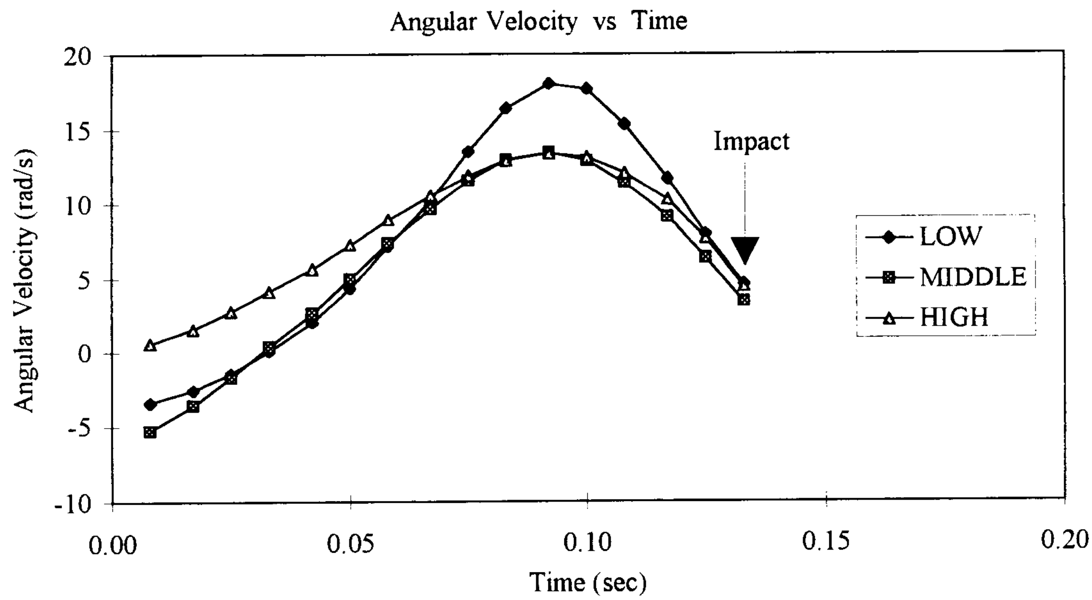

Figure 65. Angular velocity of the knee at three height levels for Subject 7.

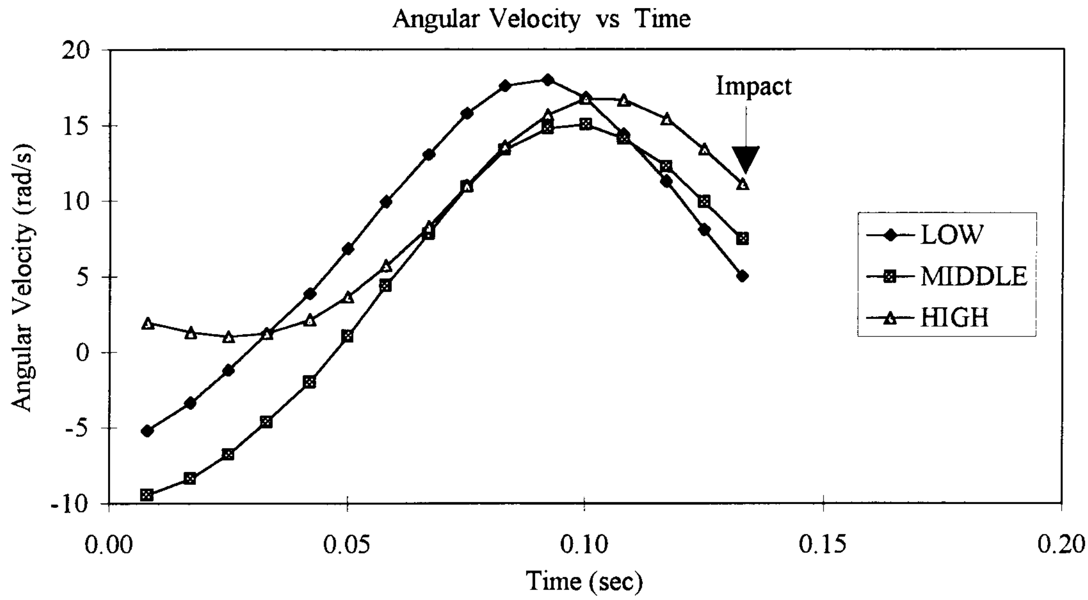

Figure 66. Angular velocity of the knee at three height levels for Subject 8.

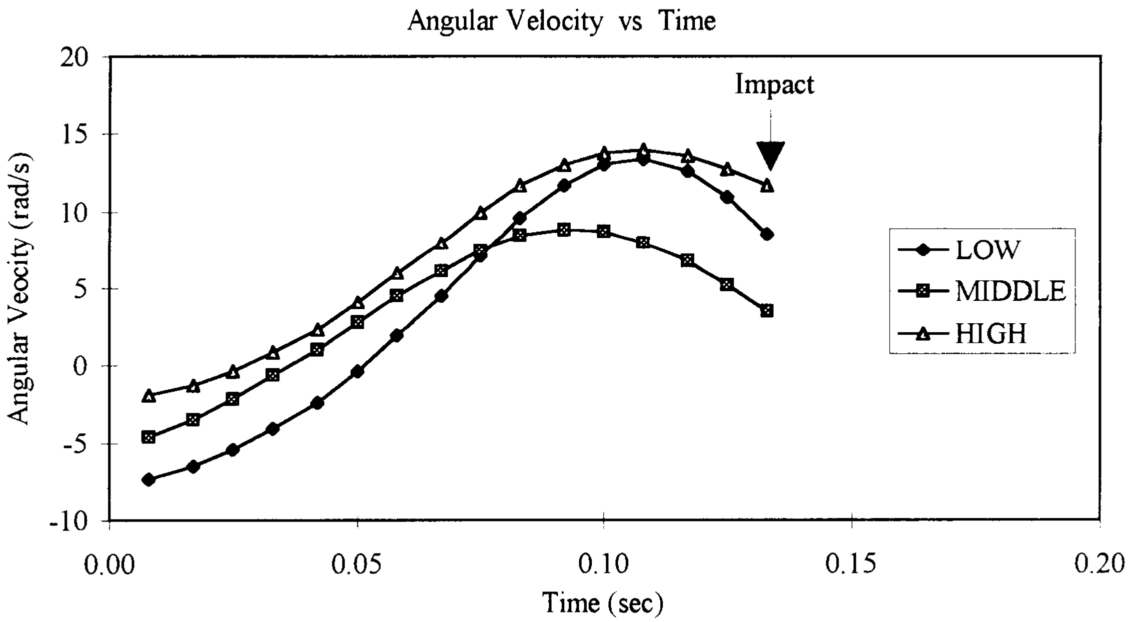

Figure 67. Angular velocity of the knee at three height levels for Subject 9.

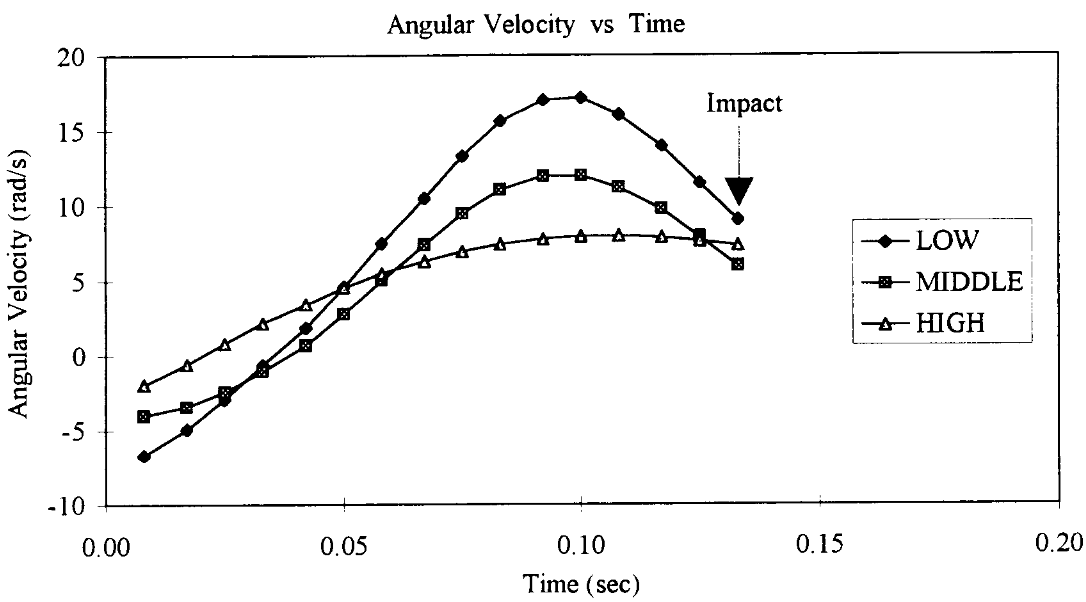

Figure 68. Angular velocity of the knee at three height levels for Subject 10.

APPENDIX K

Individual subjects' angular velocity of the shank projected onto the horizontal plane at three different height levels

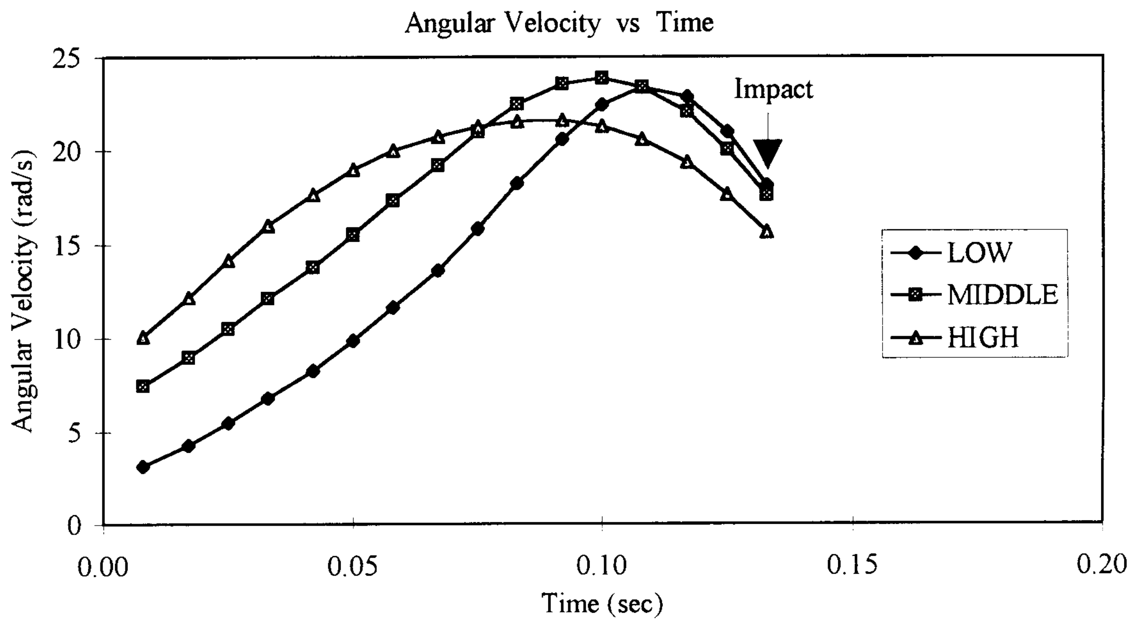

Figure 69. Angular velocity of the shank projected onto the horizontal plane at three height levels for Subject 1.

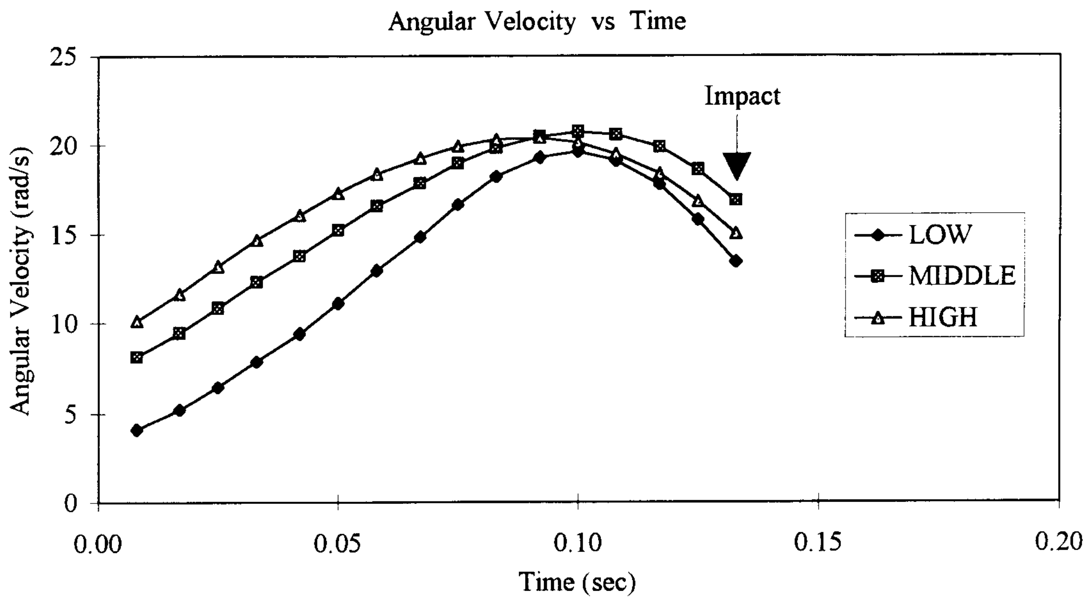

Figure 70. Angular velocity of the shank projected onto the horizontal plane at three height levels for Subject 2.

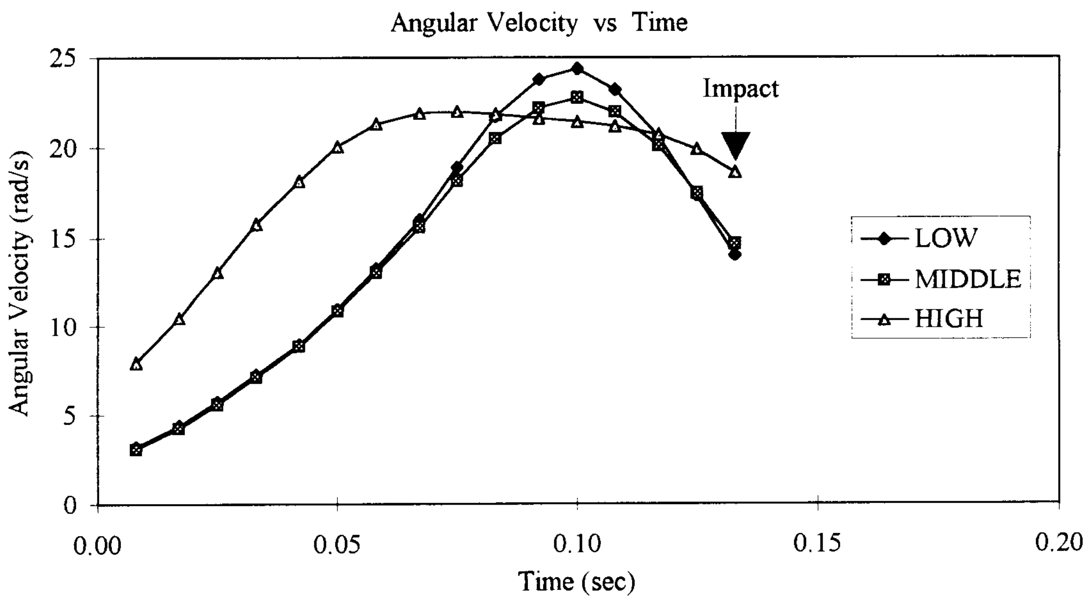

Figure 71. Angular velocity of the shank projected onto the horizontal plane at three height levels for Subject 3.

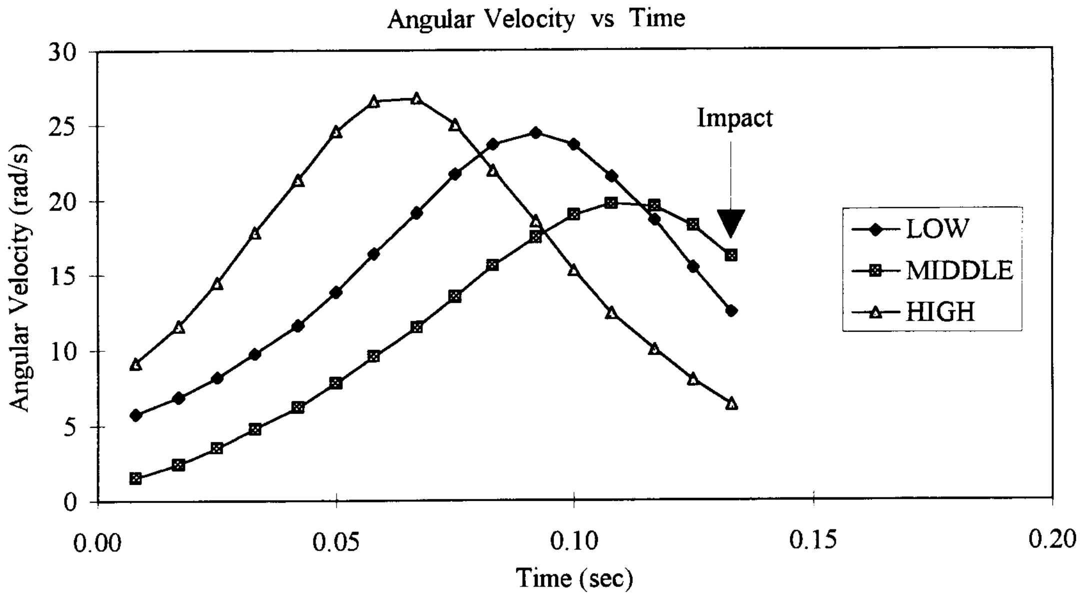

Figure 72. Angular velocity of the shank projected onto the horizontal plane at three height levels for Subject 4.

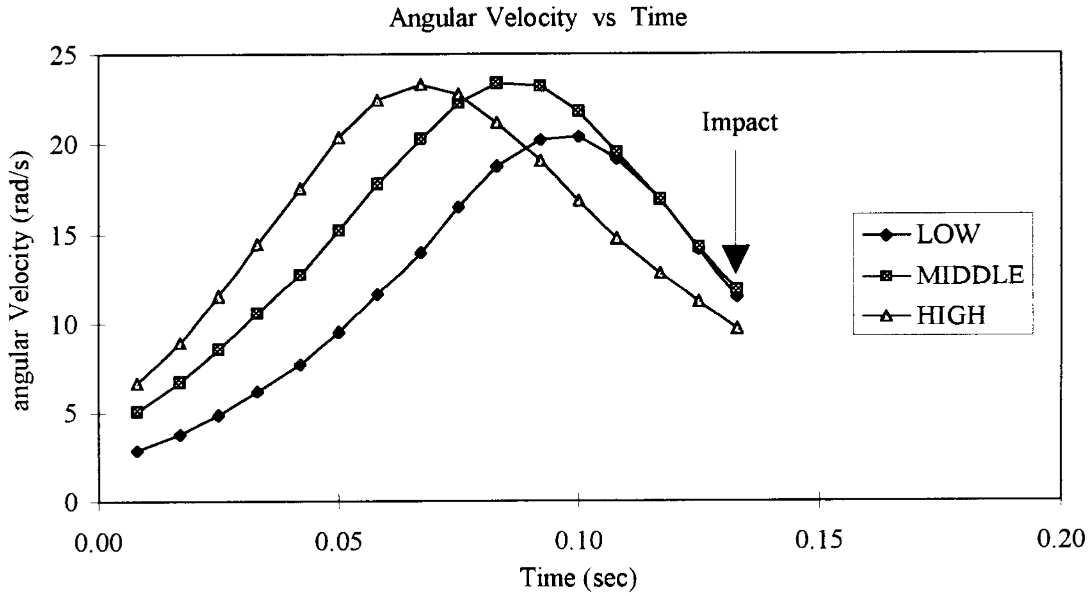

Figure 73. Angular velocity of the shank projected onto the horizontal plane at three height levels for Subject 5.

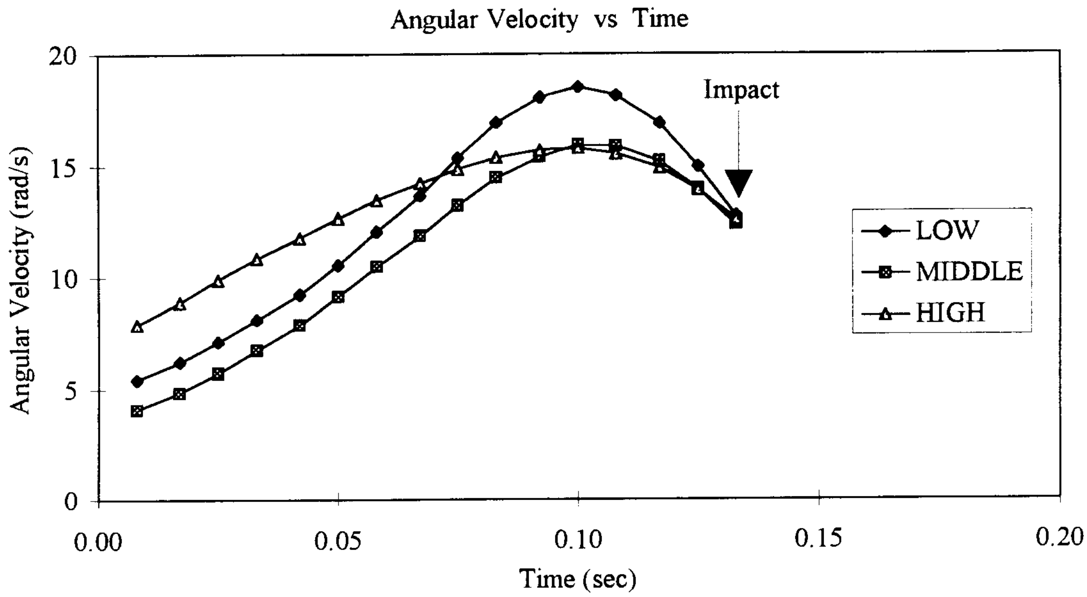

Figure 74. Angular velocity of the shank projected onto the horizontal plane at three height levels for Subject 6.

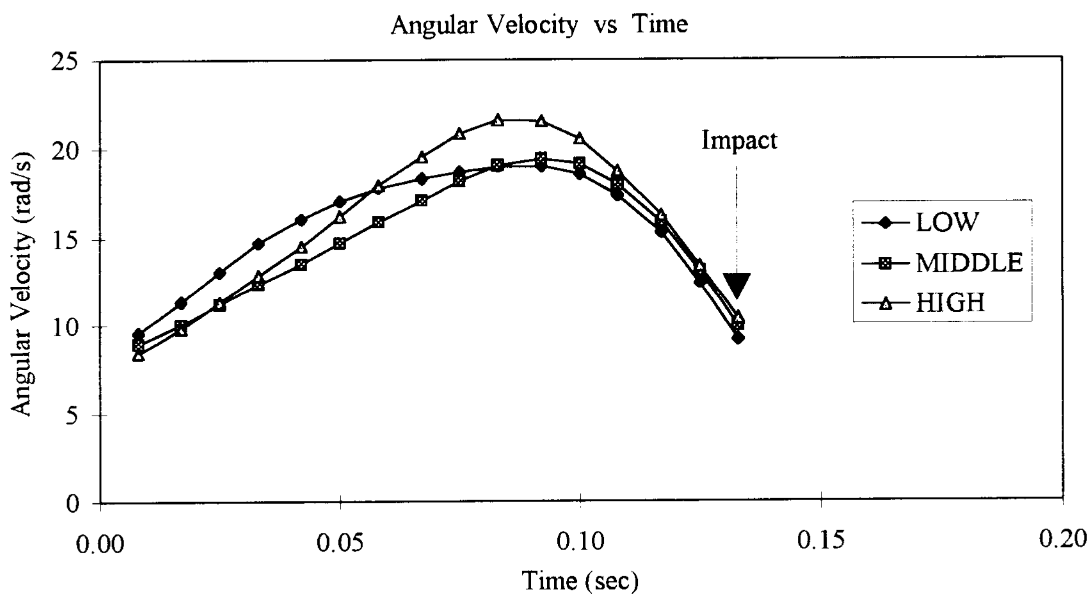

Figure 75. Angular velocity of the shank projected onto the horizontal plane at three height levels for Subject 7.

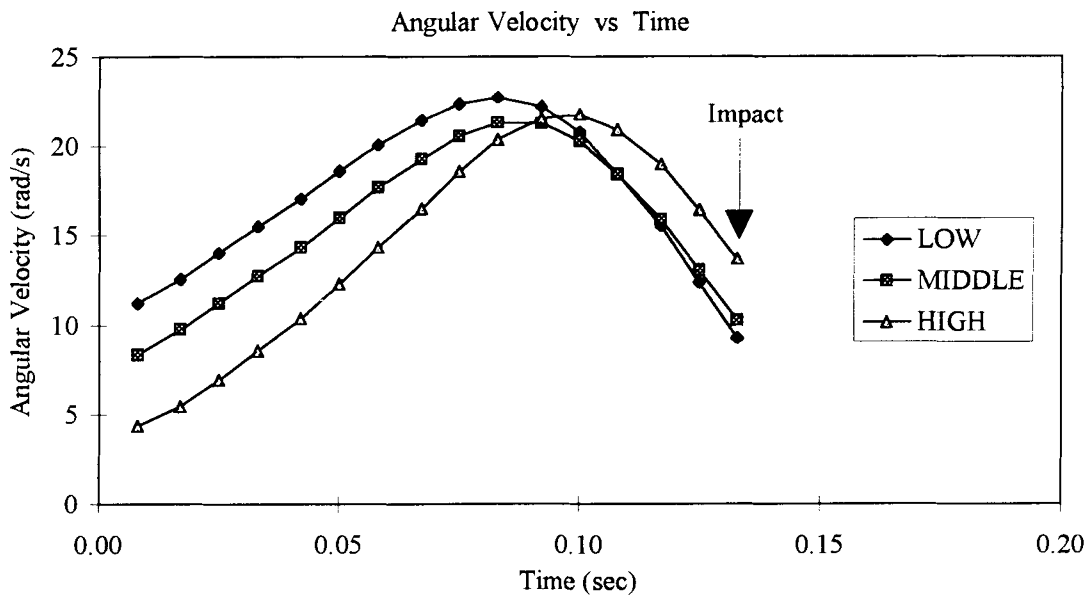

Figure 76. Angular velocity of the shank projected onto the horizontal plane at three height levels for Subject 8.

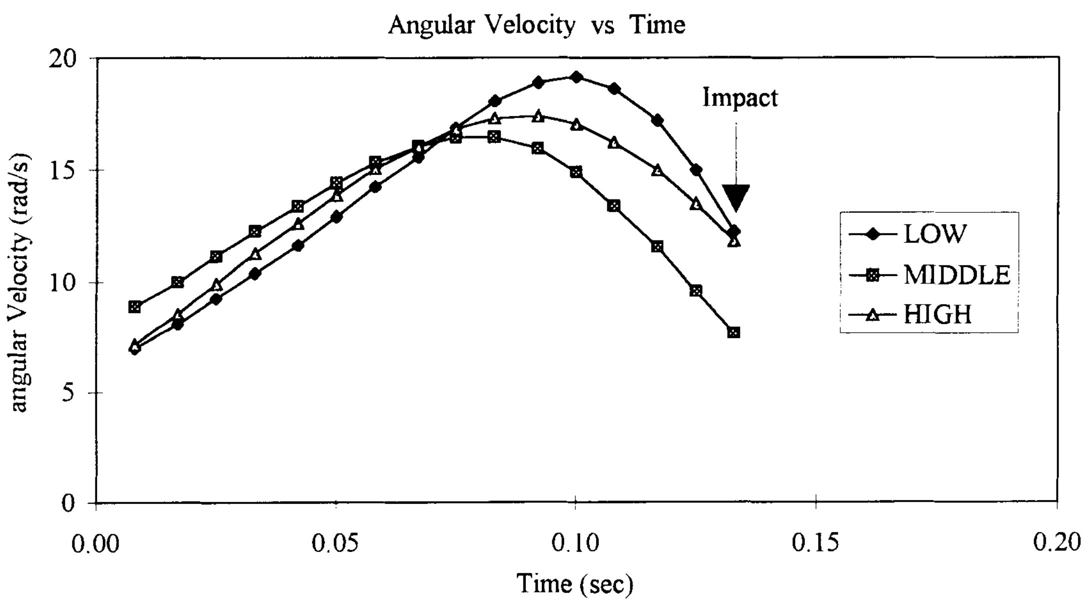

Figure 77. Angular velocity of the shank projected onto the horizontal plane at three height levels for Subject 9.

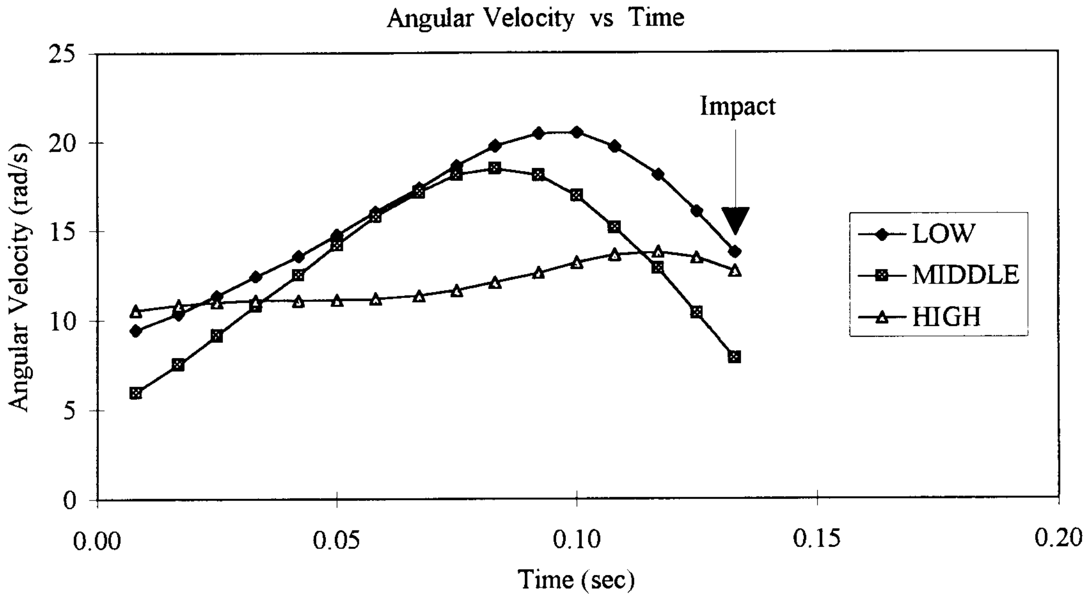

Figure 78. Angular velocity of the shank projected onto the horizontal plane at three height levels for Subject 10.

APPENDIX L

Individual subjects' angular velocity of the thigh projected onto the horizontal plane at three different height levels

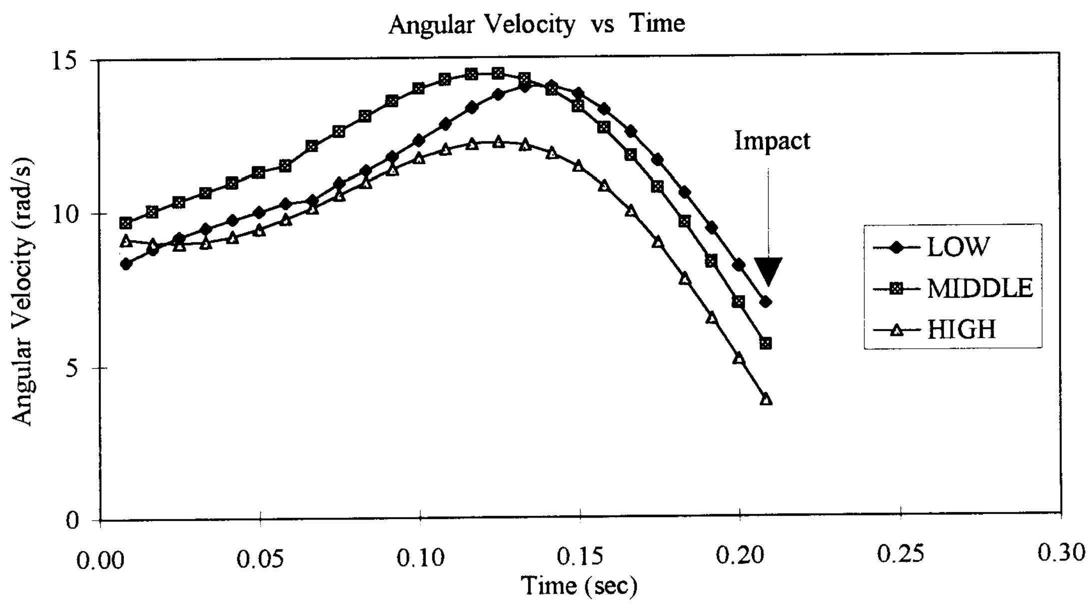

Figure 79. Angular velocity of the thigh projected onto the horizontal plane at three height levels for Subject 1.

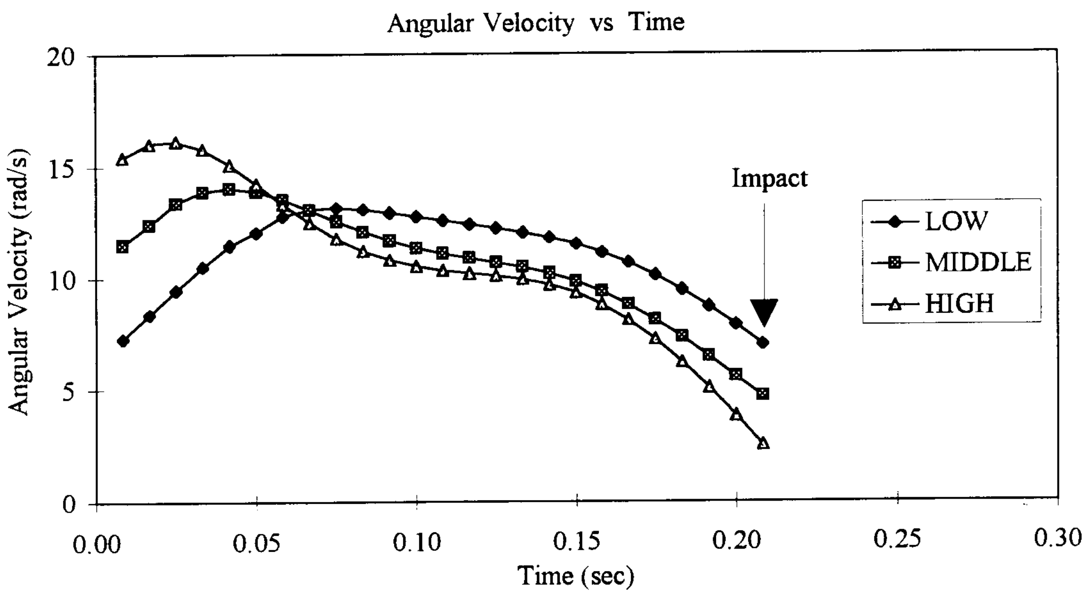

Figure 80. Angular velocity of the thigh projected onto the horizontal plane at three height levels for Subject 2.

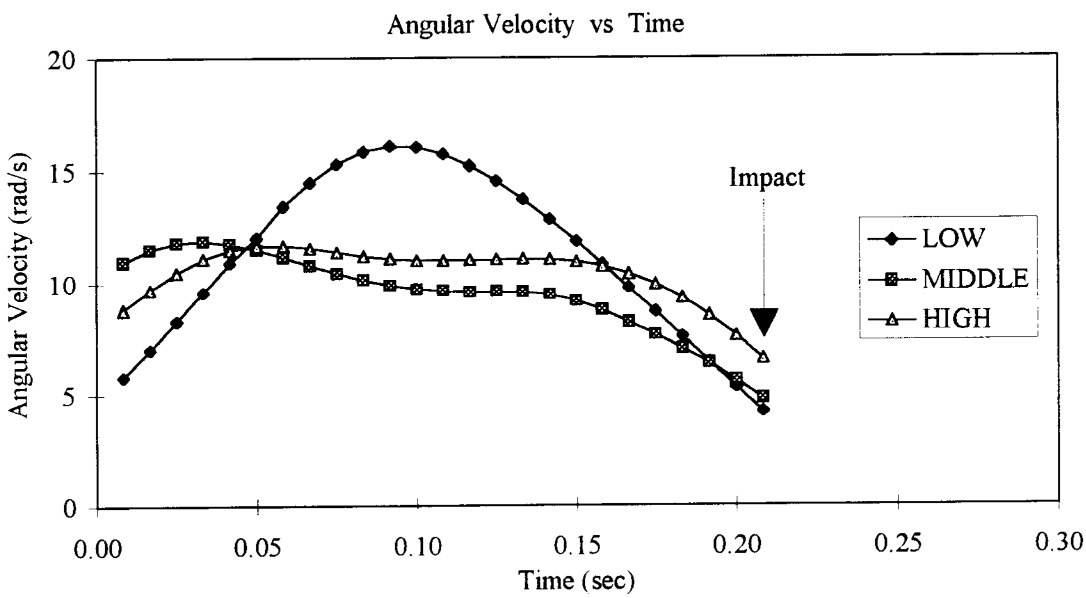

Figure 81. Angular velocity of the thigh projected onto the horizontal plane at three height levels for Subject 3.

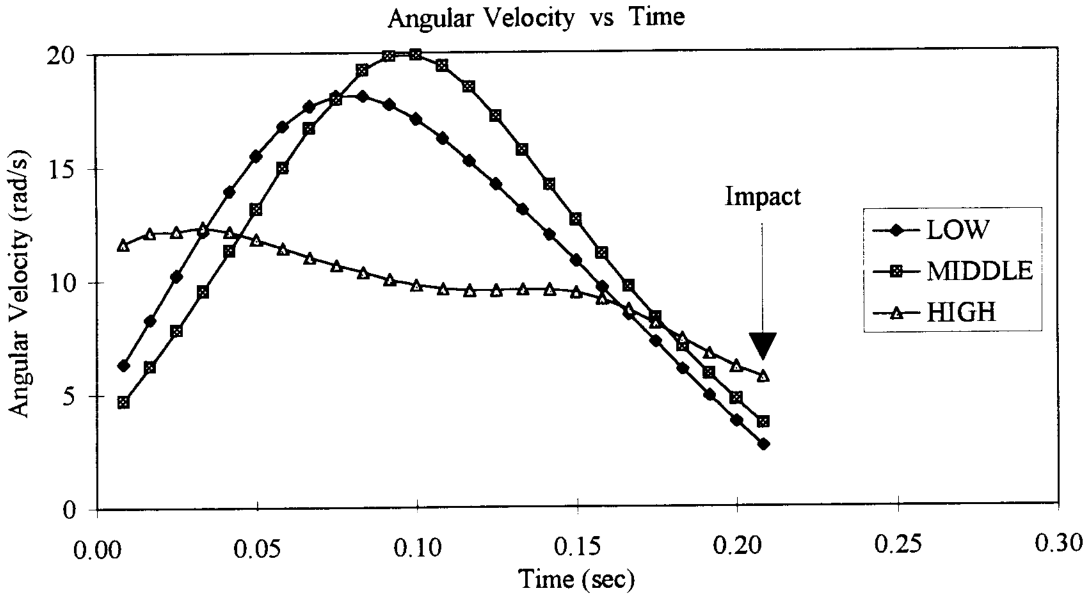

Figure 82. Angular velocity of the thigh projected onto the horizontal plane at three height levels for Subject 4.

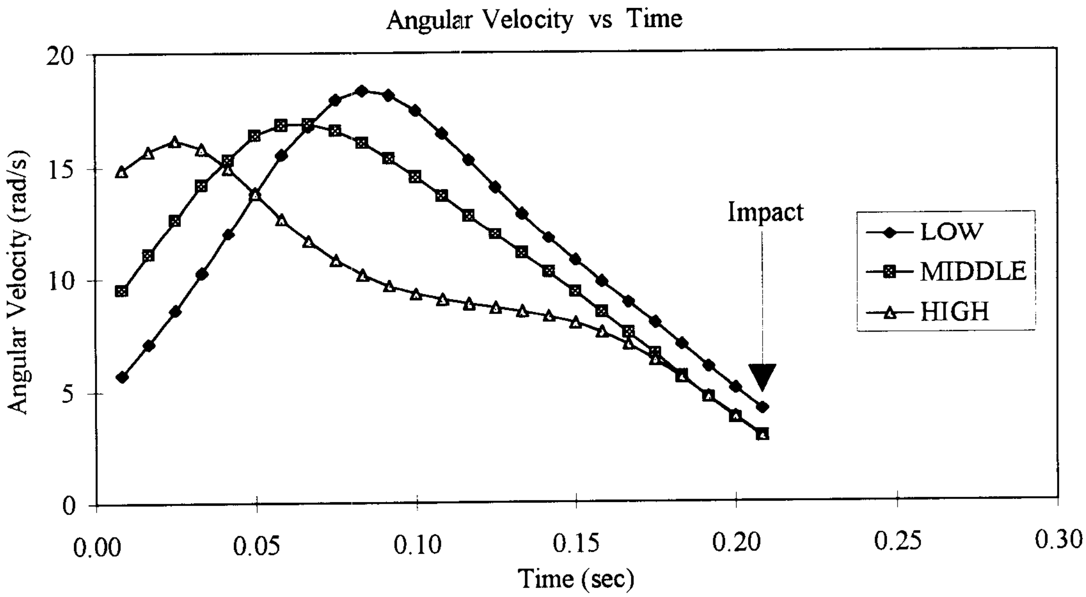

Figure 83. Angular velocity of the thigh projected onto the horizontal plane at three height levels for Subject 5.

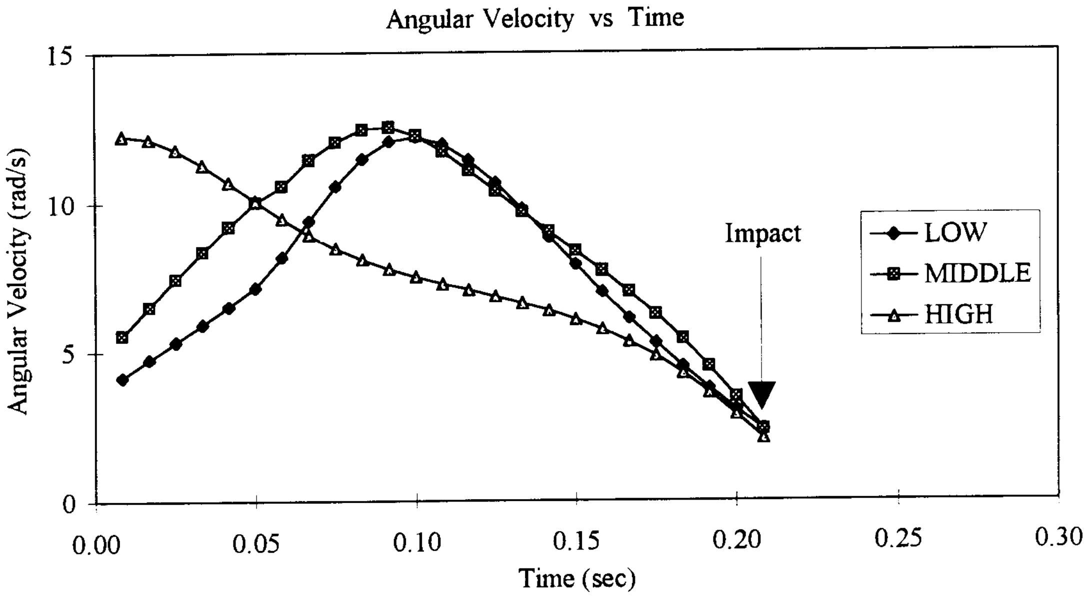

Figure 84. Angular velocity of the thigh projected onto the horizontal plane at three height levels for Subject 6.

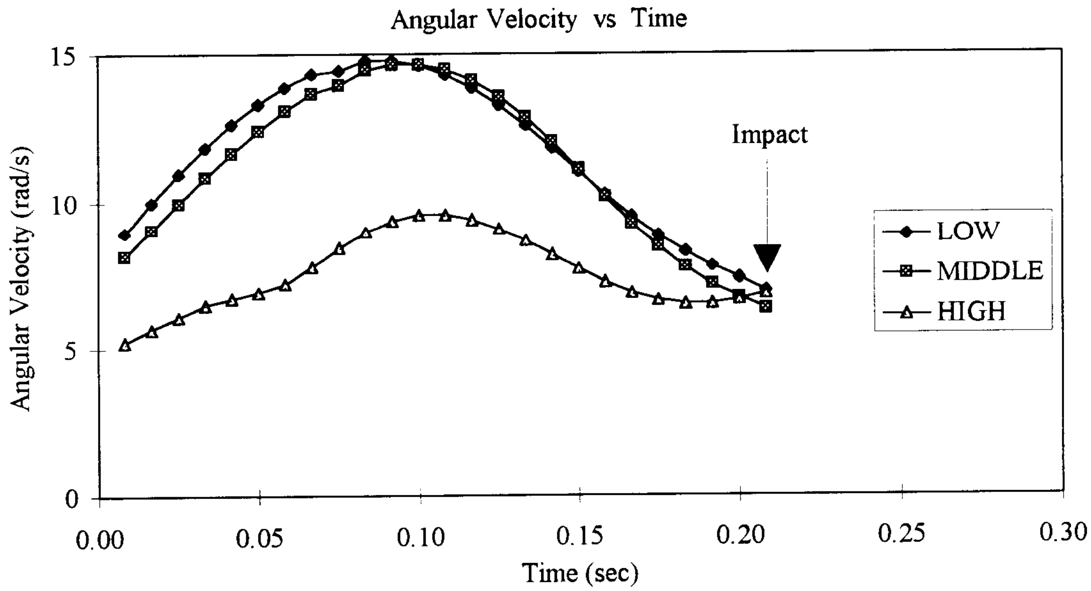

Figure 85. Angular velocity of the thigh projected onto the horizontal plane at three height levels for Subject 7.

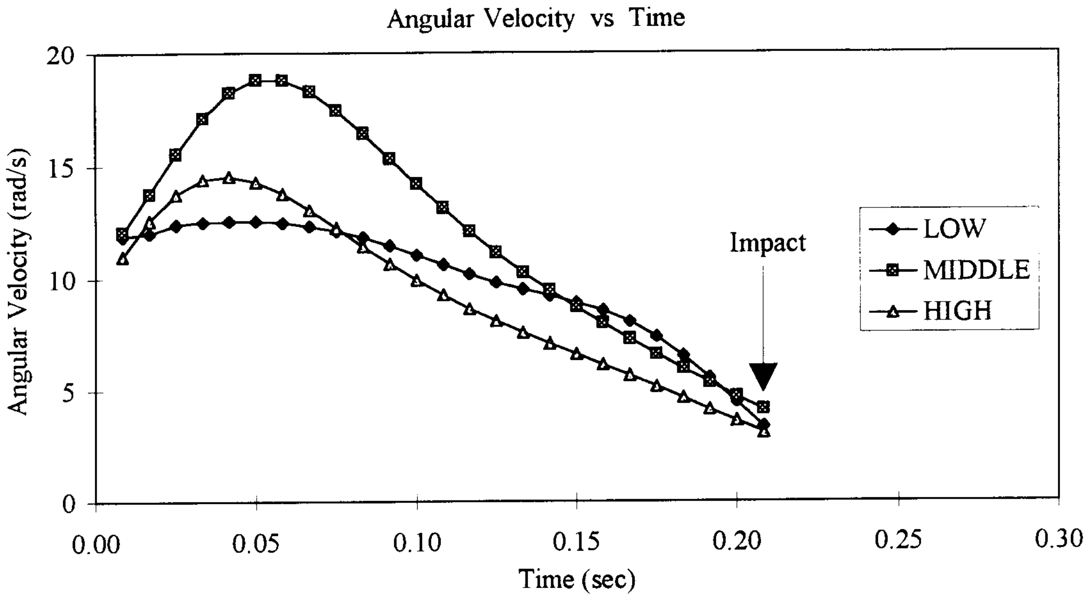

Figure 86. Angular velocity of the thigh projected onto the horizontal plane at three height levels for Subject 8.

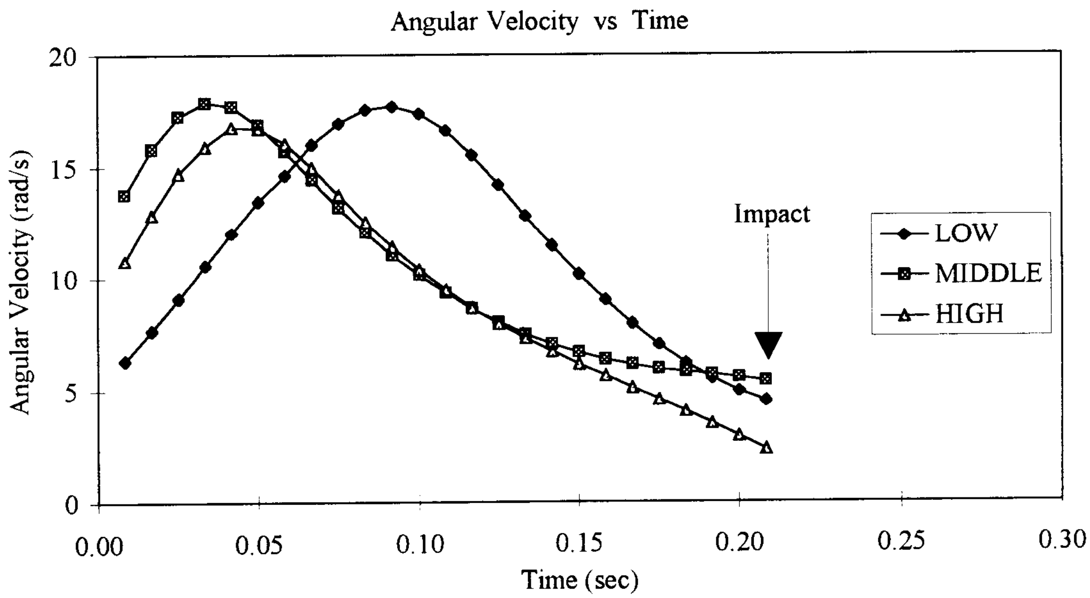

Figure 87. Angular velocity of the thigh projected onto the horizontal plane at three height levels for Subject 9.

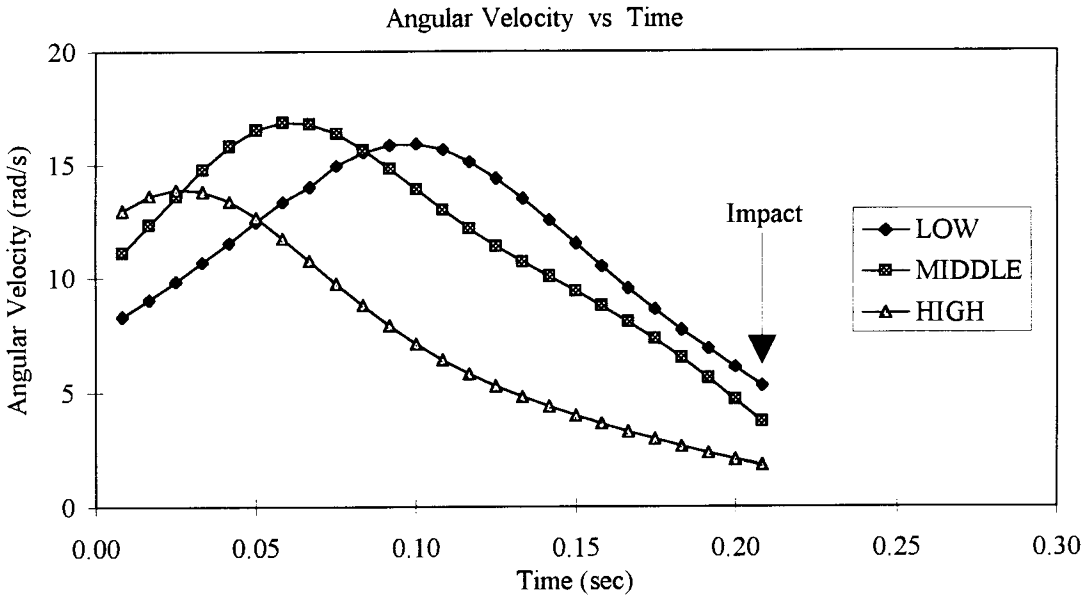

Figure 88. Angular velocity of the thigh projected onto the horizontal plane at three height levels for Subject 10.