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The role of the lower leg in determining vertical jump height

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THE ROLE OF THE LOWER LEG IN DETERMINING VERTICAL JUMP HEIGHT

A Thesis
Presented to
the Faculty of the Department of
Human Performance
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In Partial Fulfillment
of the Requirements for the Degree
Master of Arts

By
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ABSTRACT

THE ROLE OF THE LOWER LEG IN DETERMINING VERTICAL JUMP HEIGHT

by Bryan K. McCoy

Few studies (Bangerter, 1967; Hubley & Wells, 1983) identify the importance of the lower leg in vertical jumping. Thirty active college students performed maximal vertical jumps. Kinetic and kinematic data were collected via a Kistler force plate synchronized with a Peak Performance Three Dimensional Motion Measurement System. Ankle power, torque, angular velocity and angles about the ankle were calculated and correlated to vertical jump height. Analysis of covariance and Tukey post hoc tests were performed to identify group differences.

Significant correlations existed between ankle torque, ankle power and jump height, as well as between ankle torque and ankle power. Significant differences were found between the high jumping group and the average and low groups for ankle torque and ankle power. This study concluded the lower leg was important in vertical jumping. To improve jump height it is recommended that one increase torque about the ankle.

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CHAPTER 1

Introduction

Vertical jumping ability is of great value to an athlete involved in such sports as football, gymnastics, basketball, volleyball, and baseball. The capability of a player to jump higher and quicker than his or her opponent is important in order to be a successful athlete. Previous studies have been done to better understand jumping and to determine which components were responsible for an optimal jumping performance (Aura & Viitasalo, 1989; Bobbert & Van Ingen Schenau, 1988; Hudson 1986; Pandy & Zajac, 1991). Some of the variables studied in previous research were: the eccentric and concentric contact forces, time elapsed between the eccentric and concentric contraction phases (Aura & Viitasalo, 1989), order of muscle activation (Pandy & Zajac, 1991), velocity of the body's center of mass at takeoff body (Bobbert & Van Ingen Schenau, 1988), and power produced about the joints of the body (Bobbert & Van Ingen Schenau, 1988).

An optimal vertical jump was dependent upon the body's center of mass achieving maximum velocity at takeoff via a proximal to distal order of muscle activation (Pandy & Zajac, 1991). The production of high ground reaction forces during the eccentric and concentric contact phases, along with letting as little time as possible elapse between the contraction phases, were further requirements of an optimal jump (Yessis & Hatfield, 1986). Furthermore, a high work output in the joints of the lower body over a small period of time was required in the performance of an optimal jump (Bobbert & Van Ingen Schenau, 1988).

Other studies have investigated vertical jumping using different types of jumps. One legged and two legged jumps (Van Soest, Roebroeck, Bobbert, Huijing, & Van Ingen Schenau, 1985), jumps with the knee and the hip in an extended position (Yamazaki, Suzuki, & Mano, 1989), squat jumps and countermovement jumps (Fukashiro & Komi, 1987), and jumps preceded by a drop from various heights (Bobbert, Mackay, Schinkelshoek, Huijing, & Van Ingen Schenau, 1986), were compared. Additional studies have addressed the use of plyometrics as a way of improving vertical jump height (Bedi, Cresswell, Engel, & Nicol, 1987; Brown, Mayhew, & Boleach, 1986; Clutch, Wilton, McGown, & Bryce, 1983).

No studies have reported how the lower body function varies in jumpers of different abilites.

Statement of the Problem

Very few studies have made it a point to investigate the role and importance that lower extremity joint contributions play in the performance of a vertical jump, specifically that of the ankle. As a result the literature contributing to the body of knowledge on this subject has been limited. With the exception of Bangerter (1967), the studies were done with no practical application in mind. The authors of the few studies pertaining to this subject neglected to mention how the results could be applied to an athlete's training program and possibly help to improve vertical jumping performance.

Additionally, the findings of the authors were not in agreement. Miller and East (1976) calculated the average contribution of the lower leg to be 5.3%, while Luhtanen and Komi (1978) and Hubley and Wells (1983) reported 23% and 22% contributions for the lower leg, respectively. Bangerter (1967) reported the lower leg made no significant contribution to vertical jumping. Conversely, Hubley and Wells (1983) found the lower leg to be an important contributor to a maximal vertical jump.

Some of the descrepancies of the findings in the previous studies were possibly due to measurement problems resulting from the techniques the authors used to analyze the problem. It was the opinion of Hubley and Wells (1983) that the techniques used by Miller and East (1976) and Luhtanen and Komi (1978) influenced their results. Finally, the jumping abilities of the subjects participating in these studies were not mentioned, nor do the investigators use groups of different jumping abilities to see how the individual joint contributions vary among jumpers of various abilities.

Significance

The results of this study will serve to clarify the conflicting conclusions of the previous studies relative to the contribution of the lower leg in vertical jumping. In addition, information pertaining to lower leg power production among jumpers of varying skill shall be generated. Based on the results from this study, suggestions will be made as to which methods, such as squats, heel raises, or use of frontal shoes, would be best for improving vertical jumping ability.

Purpose of the Study

The purpose of this study was to gain insight into and describe the relationship between power production about the ankle and vertical jump height. The differences between groups for ankle power production were reported and the discussion following provided an explanation for any differences that were found between the groups. The data provided additional knowledge to the existing body of information concerning vertical jumping. In addition, the data contributed to the body of knowledge about lower leg function in jumpers of varying ability, which was an area that had not been previously investigated.

Null Hypothesis

This researcher hypothesized that there would be no significant relationship between power production in the lower leg and vertical jump height. Additionally, there would be no significant differences between the high, average, and low groups for lower leg power production.

Definitions

Angular acceleration- "The rate at which a body's angular speed or direction is changed." (Kreighbaum & Barthels, 1990, p. 517).

Angular velocity- "A rotating body that has speed and direction." (Kreighbaum & Barthels, 1990, p. 517).

Biarticular muscle- "A muscle that crosses two joints." (Bobbert & Van Ingen Schenau, 1986a, p. 888).

Catapult Action- "The release of stored elastic energy via the Achilles tendon shortening." (Hof, Geelen, & Van Den Berg, 1983, p. 524).

Effective energy- "The sum of potential energy and kinetic energy of the body's center of mass." (Bobbert & Van Ingen Schenau, 1988, p. 257).

Kinematic- "The description of the nature of the motion." (Hay & Reid, 1988, p. 114).

Kinetics- "The explanation of the causes of motion." (Hay & Reid, 1988, p. 143).

Kinetic energy- "The energy that a body possesses because it is in motion." (Hay & Reid, 1988 p. 172).

Mean angular velocity- "The average angular ankle velocity produced field by field during the push-off phase of a vertical jump."

Mean ankle power- "The average ankle power produced field by field during the push-off phase of a vertical jump."

Mean ankle torque- "The average ankle torque produced field by field during the push-off phase of a vertical jump."

Moment- "The product of the force and the perpendicular distance from its line of action to that point." (Kreighbaum & Barthels, 1990, p. 138).

Monoarticular muscle- "A muscle that crosses one joint." (Bobbert & Van Ingen Schenau, 1988, p. 257).

Peak angular velocity- “The maximum angular ankle velocity value produced in a field during the push-off phase of a vertical jump.”

Peak ankle power- “The maximum ankle power value produced in a field during the push-off phase of a vertical jump.”

Peak ankle torque- “The maximum ankle torque value produced in a field during the push-off phase of a vertical jump.”

Pennation- "The angle between the long axis of the muscle and the fiber angle." (Winter, 1990, p. 68).

Power production- "The power generated by a moment and the angular velocity of the rigid body." (Winter, 1990, p. 273).

Potential energy- "The capacity of an object to perform work because of its position above the earth." (Hay & Reid, 1988, p. 172).

Total ankle power- “The sum of the power values produced in each field during the push-off phase of a vertical jump.”

Assumptions

Subjects gave maximal efforts while performing the vertical jump trials and had no difficulty jumping off of both feet. Conditions under which the data were gathered were the same for all subjects.

Delimitations

1. This study was restricted to the kinetic variable of power production.
2. The jump situations involved only the legs.
3. Subjects were males and females between the ages of 18 and 25 years.

4. Jumps occurred off of two feet.

Limitations

Although power production of the lower leg was related to vertical jump height, this variable may not be highly related to vertical jump height in females or males under the age of 18 years and over the age of 25 years. Additionally, because power production of the lower leg differed between groups of various jumping abilities, no differences may be found in groups of males and females under the age of 18 years and over the age of 25 years. The body composition of the subjects was not taken into account and the results could have been affected.

CHAPTER 2

Review of Literature

Introduction

The research literature on vertical jumping has primarily investigated kinetic and kinematic variables dealing with the body as a whole. The focus of investigation has rarely been on the contribution of each body segment, especially the lower leg. The purpose of this literature review was to establish the lower leg's potential for contributing to vertical jumping. This chapter presented literature addressing biomechanical and physiological characteristics of the triceps surae. The chapter was arranged into the following subtopics: (1) studies addressing and quantifying lower leg contribution to vertical jumping, (2) studies discussing the coordination of body segments in vertical jumping, (3) studies noting the functions of the triceps surae during jumping, (4) physiological properties of the triceps surae, and (5) summary.

The lower leg contribution to jumping

In a study by Hubley and Wells (1983), five male university students performed four maximal vertical jumps, two with a countermovement and two from a static squat starting position. The hands of the subjects were placed on their hips to eliminate the contribution of the arms to the jump. Data from the jumps were collected via a force platform and Locam camera, filmed at 50 fps perpendicular to the sagittal plane of the subject. Using a work energy approach, which consisted of calculating the net mechanical work performed about the joint, Hubley and Wells (1983) found that on average 23% of the total work performed by the lower body when jumping was done by the muscles crossing the ankle joint.

Using a segmental and isolation technique, similar findings were noted by Luhtanen and Komi (1978), who calculated that plantar flexion contributed 22% to takeoff velocity. Subjects were eight male athletes who performed seven different isolated segmental jump movements and one true vertical jump. Data were collected from a force platform and filming was done at a right angle to the subjects with a Locam 51-0003 camera operating at 100 fps.

Miller and East (1976) also used a segmental technique and found the percent contributions of segmental inertial forces for the lower legs to be 5%, 4.7%, 7.2%, and 4.4% respectively, for the four subjects in the study. Subjects consisted of four college-aged women (20-23 yr.) who performed eight maximal vertical jumps. The jumps were performed on a Kistler Force Platform (type 9261A) while being simultaneously filmed laterally with a Locam camera at 98.4-98.9 fps.

The earliest investigation focusing on the contributive components of the lower body in jumping was by Bangerter (1967). This study was based on the assumption that if a muscle group contributing to vertical jumping was strengthened, then vertical jump performance would improve. Subjects were 112 college-aged males who were randomly assigned to four groups. Three groups performed resistance exercises of plantar flexion, knee extension, and hip extension. The fourth group performed all three exercises. The progressive resistance exercise of one set of eight to twelve repetitions was performed three times a week for eight weeks. The post training vertical jump test results were that the subjects in the plantar flexor strengthening group and control group did not display a significant jump height increase compared to their pre-training vertical jump test. The author then concluded that the plantar flexors did not contribute significantly to vertical jumping.

Coordination of Body Segments

Coordination is believed to be a necessary component in an efficient performance of a motor skill. In a skill such as jumping, where takeoff velocity determines the jump height achieved, a sequential segment movement pattern prevails. Pandy, Zajac, Sim, and Levine (1990), using a musculoskeletal model, found that an effective jump performance required that the hip extensors, gluteus maximus, and hamstrings be activated first; followed by activation of the knee extensors, vasti group and rectus femoris. The final activation occurs in the soleus, gastrocnemius, and the other plantar flexor muscles. Bobbert and Van Ingen Schenau (1988), and Gregoire, Veeger, Huijing, and Van Ingen Schenau (1984) reported similar findings.

Van Ingen Schenau (1989) studied subjects performing two legged maximal jumps while the subjects kept their hands on their hips. Electromyography was recorded for the semitendinosus, gluteus maximus, rectus femoris, vastus medialis, gastrocnemius (medial head) and soleus muscles. Subjects were filmed at right angles with a 16 mm high speed camera operating at 100 fps. Ground reaction forces were measured via a force plate, in addition to a model consisting of rigid link segments representing the ankle, shank, thigh, and trunk. Results were hip extension, knee extension and plantar flexion occurred in a sequential, proximal to distal pattern beginning 300 milliseconds (ms), 200 ms, and 100 ms, respectively, before toe-off. Muscle activity increased in the gluteus maximus and hamstrings between 400 ms and 300 ms, the vasti group and rectus femoris between 300 ms and 200 ms, and the plantar flexors between 200 ms and 100 ms before toe-off.

Similar findings demonstrating a sequential proximal to distal muscle activity pattern were noted in a study by Bobbert and Van Ingen Schenau (1988). Subjects were ten males, aged 20-26 years, who performed maximal two legged jumps with a countermovement while keeping their hands on their hips. Filming was done at a right angle to the subject with a 16 mm high speed Teledyne type DBM55 camera operating at a rate of 100 Hz. Boney landmarks were the fifth metatarsophalangeal joint, lateral malleolus, knee joint, greater trochanter, and neck (fifth cervical vertebrae). Electromyography data were gathered for the biceps femoris, vastus medialis, medial head of gastrocnemius, and soleus muscles. Reaction forces were recorded using a Kistler type 9281B Force Plate. The results were that at the start of the toe-off phase the gluteus maximus was fully active, the vastus medialis was 62% active, and the soleus was 26% active.

Though an effective jumping performance involved a sequential movement pattern, it was critical that the time elapsing between segment movements was kept minimal. Hudson (1986) had subjects (10 male and 10 female) aged 19-26 years perform maximal vertical jumps in static jump and countermovement conditions. Subjects were filmed perpendicular to their sagittal plane with a 16 mm Locam camera at 101.9 fps. Points digitized corresponded to the shoulder, elbow, wrist, hip, knee, ankle, and fifth metatarsalphalangeal joints on the subject's right side. Skilled subjects had a proximal to distal initiation of extension with approximately 25 ms delays between adjacent segments, while the least skilled subjects' initiation of extension was frequently not proximal to distal. The time delays for the less skilled subjects were often greater than 60 ms.

In a study by Pandy and Zajac (1991), five male subjects aged 20-24 years performed maximal two legged vertical jumps from a squatting position with their hands on their hips. Data consisting of ground reaction forces, limb motion, and EMG were recorded simultaneously for three consecutive jumps. An AMTI six component strain gauge force platform was used to measure ground reaction forces. Horizontal and vertical reactions were sampled at 1000 Hz, as were the analog EMG data. Surface electrodes were placed on the right lower extremity of each subject to record activity in the soleus, gastrocnemius, tibialis anterior, quadriceps, hamstrings, and gluteus maximus. Limb motion was recorded by the placement of light emitting diodes on the fifth metatarsophalangeal joint, calcaneus, lateral malleolus, lateral epicondyle, greater trochanter, and glenohumeral joint. According to Pandy and Zajac (1991), the goal of the sequential pattern in vertical jumping was to maximize the effective energy of the body's center of mass at takeoff. These investigators found the lower extremity muscles acted to transfer energy to the most massive body segments during propulsion. Conversely, Van Soest, Schwab, Bobbert, and Van Ingen Schenau (1993) and other previous research (Bobbert & Van Ingen Schenau, 1988; Bobbert, Huijing, & Van Ingen Schenau, 1986b) found energy to flow from proximal to distal body segments.

The amount of effective energy at toe-off determines maximum jump height (Van Ingen Schenau, 1989). Bobbert and Van Ingen Schenau (1988) reported that to provide the body's center of mass with a high effective energy at toe-off, and ensure a maximal distance between the body's center of mass and the toes at takeoff, it is necessary that the vertical velocity differences between the ends of the segments attain their peaks in a proximal to distal sequence. The ability of the foot to plantar flex is important. Bobbert and Van Ingen Schenau (1988) found as the velocity difference drops between the body's center of mass and ankles, the increase in vertical velocity difference between the ankles and metatarsal heads, due to plantar flexion, dominated, and resulted in a continuing acceleration of the body's center of mass relative to the ground.

Bobbert and Van Ingen Shenau (1988) reported the proximal to distal attainment of peak velocity differences between body segments allowed the jumper's foot to maintain contact with the ground. If a premature toe-off occurred a lower effective energy of the body's center of mass would result because the shortening capacity of the hip and knee extensors would not be fully optimized due to the jumper losing contact with the ground well before the hip and knee were fully extended.

Pandy and Zajac (1991) found that plantar flexion accounted for 90% of the ground contact time. Plantar flexion also allowed the foot to stay in contact with the ground, instead of losing contact at the instant the vertical velocity differences between the body's center of mass and ankles peaked. Van Ingen Schenau (1989) reported loss of ground contact would make the further acceleration of the body's center of mass impossible. Van Ingen Schenau (1989) found that during plantar flexion, 50 ms to 60 ms before toe-off, the kinetic energy was increased by more than 50% along with an increase in potential energy. Van Ingen Schenau (1989) also noted that the flight phase in maximal jumping was determined by the amount of effective energy at toe-off.

Tricep Surae Functions In Jumping

During jumping, peak power output at the ankle reached values as high as 2500 Watts (W) (Van Ingen Schenau, Bobbert, Huijing, & Woittiez, 1985) and 3000-4000 W (Gregoire et al., 1984). Under certain conditions of plantar flexion the amount of power output from the ankle varied.

De Graaf, Bobbert, Tettero, and Van Ingen Schenau (1987) had 11 subjects aged 20-26 years perform one legged maximal jumps under two types of conditions. One was a one legged jump with preparatory countermovement and the other was a one legged jump with an extended knee. In both jump conditions subjects kept their hands on their hips. Subjects were filmed in the sagittal plane with 16 mm film at 100 fps and ground reaction forces were measured with a Kistler type 9821B Force Plate. Electromyography data were collected for the soleus and lateral and medial gastrocnemius. A model of the triceps surae complex was developed to aid in the description of the force velocity relationship of the muscle fibers, force-elongation relationship of tendinous tissue, and the relationship between rate of change of force and rate of change of tendon length. De Graaf et al. (1987) reported that in a one legged countermovement jump, the ankle power production was 1404 W, and that in a one legged jump with an extended knee ankle power production was 852 W.

Van Soest et al. (1985) had 10 male volleyball players perform maximal one legged and two legged vertical jumps with preparatory countermovement. Subjects kept their hands on their hips during the jump. Data were collected via a Kistler 9281B Force Plate, while filming was done with 16 mm film at 100 fps. Van Soest et al. (1985) reported a peak power output of 1794 W about the ankle in a one legged countermovement jump, and a peak power output of 1217.5 W about the ankle in a two legged jump. Van Ingen Schenau et al. (1985) found a peak power output of 2499 W about the ankles in a two legged squat jump using similar methodologies as Van Soest et al. (1985), with the exception that subjects were allowed no countermovement. These values were considerably higher than the 214 W produced in isokinetic plantar flexion (Fugl-Meyer, Kjell, & Hornsten, 1982), in which 10 highly active males aged 20-24 years performed isokinetic plantar flexion at 30, 60, 120, 180, and 240 degrees per second, while in a supine position. Two Cybex dynamometers were used to measure maximum isokinetic plantar flexion torques.

The power produced in the ankles during jumping was higher than what the triceps surae can produce (Bobbert, Huijing, & Van Ingen Schenau, 1986b). It was believed the discrepancies of the ankle power outputs under the various conditions mentioned were attributable to two mechanisms: catapult action, and power transfer via the gastrocnemius (Bobbert et al., 1986b; De Graaf et al., 1987; Van Ingen Schenau et al., 1985). In jumping movements the mechanisms of catapult action and power transfer were present and were able to aid in increasing the power output about the ankle. Whereas in isokinetic plantar flexion and extended knee jump conditions, the contributions of these mechanisms were smaller, leading to lower power outputs.

A study by Bobbert et al. (1986b) had 10 male subjects, aged 19-27 years, perform maximal one legged vertical jumps using their non-dominant leg, while keeping hands on their hips. Landmarks were placed on the fifth metatarsophalangeal joint, heel, ankle, knee, hip, and neck. Subjects were filmed in the sagittal plane with a 16 mm camera at 100 fps. Ground reaction force data were measured via a Kistler type 9281B Force Plate. Data collected and calculated from the subjects were imposed on a model of the muscle-tendon complex of the triceps surae, and power contributions of the tendinous structures, muscle fibers, and transportation were calculated. Bobbert et al. (1986b) found of the 1870 W of peak power produced by the model of the triceps surae complex, the muscle fibers produced 511 W, 375 W were transported via the gastrocnemius, and the catapult action of the tendon was responsible for producing 984 W.

Anderson and Pandy (1993) described how the elastic elements of the muscles and tendons stored and contributed elastic energy to vertical jump performance. Using a musculoskeletal model and five athletic adult males aged 20-30 years, subjects performed five jumps with a countermovement and five jumps from a static squat position in alternating order, while keeping their arms crossed over their chest. Ground reaction forces were recorded using a Bertec six-component, strain gauge force plate. Electromyography was sampled at 1000 Hz. The surface EMG electrodes recorded activity in the soleus, gastrocnemius, tibialis anterior, quadriceps, hamstrings, and gluteus maximus on the right leg. Kinematic data were recorded using the

Motion Analysis Incorporated Kinematic Data Acquisition System. The fifth metatarsophalangeal joint, lateral malleolus, lateral epicondyle, greater trochanter, and glenohumeral joint were chosen as landmarks and fitted with retroreflective markers. Film rate was 60 frames per second. The ankle plantar flexors were found to contribute 25% of the total energy delivered to the skeleton during a vertical jump. Of this energy delivered to the skeleton by the plantar flexors, the elastic tissues of the plantar flexors accounted for 70% and the contractile elements accounted for only 30%. The energy delivered by the larger muscles, gluteus maximus, hamstrings, and quadriceps, was dominated by the contractile elements because the tendons of these muscles were short and stiff and not well suited for energy storage as compared to the long, compliant tendons of the plantar flexors.

Fukashiro, Komi, Jarvinen, and Miyashita (1995) investigated the behavior of the Achilles tendon under various jumping situations using a surgically implanted buckle-type transducer on the right Achilles tendon of a 30 year old man, who happened to be one of the investigators. The jumping conditions consisted of a maximal vertical jump using a countermovement, a maximal vertical jump from a squat position, and repetitive submaximal hopping. Each jump was performed three times. Electromyographical data were recorded from the lateral gastrocnemius and soleus by Beckman bipolar surface electrodes. Filming of the jumps was done in the sagittal plane with a 16mm Locam 51-0003 camera operating at 100 frames per second. Body segment coordinates defined the trunk, thigh, shank, foot, and toe. The coordinates were attained using a Vanguard Film Analyzer, Summagraphics 10 digital board and HP 21 Max computer system. It was found that the elastic energy stored in the Achilles tendon accounted for 23%, 17%, and 34% of the total work done by calf in the three jumping situations: squat jump, countermovement jump, and hopping, respectively. The investigators reasoned that previous studies overestimated the contribution from elastic energy by including gravitational and friction forces in the model for their studies.

It was the gastrocnemius function that helped to transport power to the ankle. Using models with the gastrocnemius missing Pandy and Zajac (1991), and Bobbert and Van Ingen Schenau (1988), found jump height to be lower than when the gastrocnemius was in tact. Both investigations concluded that the contribution of the gastrocnemius to jumping cannot be neglected.

Prilutsky and Zatsiorsky (1993) reported that two-joint muscles such as the gastrocnemius and rectus femoris behave in a tendon-like fashion, transferring mechanical energy between joints. Their study used five healthy males. Subjects performed vertical jumps from a deep squat, jumps down from a height of 0.5 meters, and jogging. Reflective markers were placed on the metatarsalphalangeal, ankle, knee, hip, and shoulder joints and illuminated at frequencies of 100 Hz for the jogging situation, and 50 Hz for the jump situations. Filming was done by a UMK-10 photogrammetric camera, and synchronized with the ground reaction forces collected by a PD 3-A Force Platform. The collected data were then combined with a four link model of the leg. When the leg pushes off against the ground while jumping, energy was transferred by two-joint muscles from the hip to the knee and the knee to the ankle. It was the tendon-like behavior of the two-joint muscles that allowed for the transfer of the mechanical energy. Energy transfer through the gastrocnemius was equal to about 22.8 ± 5.1% of the maximum power production at the ankle in the vertical jump situation. The amount of work a muscle can perform was proportional to its volume. The tendon behavior of the gastrocnemius assists the distal muscles of the leg, which were small in volume, in performing positive work during the vertical jump push-off by the transfer of mechanical energy.

Van Ingen Schenau, Bobbert, and Rozendal (1987) also investigated the importance of the biarticular action of the gastrocnemius during vertical jumping. Ten experienced jumpers performed two legged jumps with a countermovement. Ground reaction forces and cinematographic data were recorded via a Kistler Force Plate and filming (16 mm) at 100 fps at right angles to the sagittal plane of the subjects. Joints marked were the fifth metatarsophalangeal, ankle, knee, and hip. Electromyography was also recorded for the vastus lateralis, rectus femoris, and both heads of the gastrocnemius. It was found that the biarticular gastrocnemius enabled the knee to extend over a full range of motion while still being active to produce power, which was transported to the ankle where it was used for plantar flexion. In this way the gastrocnemius opposed knee extension which prevented hyperextension and at the same time aided plantar flexion (Van Ingen Schenau, Bobbert, & Rozendal, 1987).

In another investigation of the role of the gastrocnemius in jumping, Gregoire et al. (1984) had eight male subjects perform two legged maximal vertical countermovement jumps with their hands on their hips. Ground reaction forces were recorded with a Kistler 9281B force plate and filming was done at 100 fps utilizing a 16 mm camera. The coordinates were the tip of the foot, heel, ankle joint, knee joint, and neck. In addition EMG was recorded for the gluteus maximus, rectus femoris, vastus medialis, semitendinosus, biceps femoris, medial and lateral gastrocnemius, and soleus muscles. Results indicated that the ability of the gastrocnemius to deliver power from the knee at the end of push-off allowed the gastrocnemius to transfer internal rotational energy into translational energy of the body without energy losses due to eccentric contraction. By the gastrocnemius decelerating limb velocity with no energy loss, a more efficient push-off occurred (Gregoire et al., 1984).

The importance of the gastrocnemius being biarticular was substantiated by the following studies. Through computer modeling and simulation, Van Soest et al. (1993) showed that maximum jump height decreased by 10 millimeters when using a monoarticular gastrocnemius instead of a biarticular gastrocnemius in the model. Van Soest et al. (1993) and Leeuwen and Spoor (1992) disagreed with the conclusion of Pandy and Zajac (1991) that the ability of the gastrocnemius to increase jump performance was not a consequence of it being biarticular. They contended the simulated gastrocnemius moment arm about the knee, used by Pandy and Zajac (1991), was not accurate. This resulted in a vanishing flexor knee moment of the gastrocnemius as the knee was extending. Therefore, when the knee was close to full extension the biarticular gastrocnemius was functioning as if it were a monoarticular gastrocnemius. When the model was used with a monoarticular gastrocnemius replacement, no difference was noted in jump height.

Velocity played an important role in power production. Since power equals force multiplied by velocity, increases in velocity would yield increases in power. Zuurbier and Huijing (1992) looked at the shortening speed of fiber, muscle, and aponeurosis using the gastrocnemius muscle of a rat. Behavior was studied during isometric and isokinetic contractions by use of cinematography. The investigators reported as muscles shortened, the amount of force decreased rapidly, which resulted in the tendon shortening speed increasing relative to the muscle shortening speed. At optimal muscle lengths, fiber and tendon speed were 84% and 6% of the muscle speed, respectively. As muscle shortened, fiber speed decreased to as low as 35% of the muscle shortening speed, whereas tendon shortening speed increased up to 31% of the muscle speed (Zuurbier & Huijing, 1992).

It would seem the power lost due to the decreasing muscle force is compensated for by the increasing velocity of shortening of the tendon. De Graaf et al. (1987) noted the faster the rate of force decreased, the faster the tendinous structures shortened. Bobbert et al. (1986b) referred to tendons acting as power amplifiers, releasing energy faster than it was stored.

In comparing countermovement jumps and extended knee jumps, the peak torques produced in both types of jumps were approximately 194 Nm (Bobbert & Van Ingen Schenau, 1990; De Graaf et al., 1987). As was noted earlier in this chapter, the power produced about the ankle was greater in countermovement jumps than in extended knee jumps. This was because of the greater contribution of catapult action to the countermovement jump resulting in a greater shortening velocity, consequently more power was produced.

Zajac, Wicke, and Levine (1984) developed three dynamic models of ankle torque generation. The models were based upon known calf muscle properties, series elastic, force-length, and force velocity. Using these models maximum height jumps were simulated for humans who jumped using only their ankles for propulsion. It was found as tendon stiffness decreased, jumping height increased due to the more compliant tendon providing a longer propulsion phase.

Based on the findings of Bobbert et al. (1986b), the majority of power produced about the ankle was the result of the release of stored elastic energy from the tendon. Catapult action was an important factor in peak power production (Hof, Geelen, & Van Den Berg, 1983).

Physiological properties of the triceps surae

Johnson, Polgar, Weightman, and Appleton (1973) reported the soleus muscle to have 80% slow-twitch fibers. Sale, Quinlan, Marsh, McComas, and Belanger (1982) reported the soleus had the highest distribution (70-80%) of slow-twitch fibers of any human muscle, while the gastrocnemius had equal distribution of fast- and slow-twitch fibers.

The difference in fiber type distribution found in the soleus and gastrocnemius indicated that the gastrocnemius had a faster rate of contraction. In their investigation of contractile properties of the gastrocnemius and soleus muscles, Vandervoort and McComas (1983) had the subjects' (five men and five women aged 22-32 years) muscle groups selectively stimulated by way of electrodes, and compound action potentials were recorded from individual muscles with pairs of silver cup electrodes. The investigators found the contraction times for the lateral and medial gastrocnemius heads and the soleus to be 100 ms, 113 ms, and 156 ms, respectively. The difference in contraction speed was viewed as a result of the soleus having a higher distribution of slow-twitch fibers than the gastrocnemius.

Buller, Dormhurst, Edwards, Kerr, and Whelan (1959) demonstrated a difference in contraction speed between the human gastrocnemius and soleus. Herman and Bragin (1967) found gastrocnemius activity to be greatest during fast maximal contractions and a greater contributor to fast contractions than the soleus. The soleus appears to be designed to maximize force production at very slow shortening velocities (Wickiewicz, Roy, Powell, Perrine, and Edgerton, 1984).

Wickiewicz et al. (1984) had 12 subjects, eight males and four females aged 20 to 30 years, perform knee extension, knee flexion, ankle plantar flexion, and ankle dorsiflexion on an isokinetic dynamometer (Cybex two Lumex). The recording speeds ranged from 0 radians per second to 5.03 radians per second. Angle specific force-velocity curves were also generated. The data were then matched with the predicted maximum forces and shortening velocities derived from muscle architectural determinations made on cadavers. According to the investigators, the plantar flexors should have the greatest potential for tension production compared to the dorsiflexors, knee flexors and knee extensors because of the high number of cross bridges the plantar flexors have arranged in parallel. The plantar flexors should also have the lowest maximal linear velocities because the shortening velocities of muscle were proportional to the number of sarcomeres arranged in series. The fibers of the plantar flexors were in more of a parallel arrangement than a series arrangement. It seems the shortening velocity potential of the gastrocnemius was compromised by its fibers being in a parallel arrangement and the pennation of the fibers.

The architecture of the triceps surae suggested force, not velocity was the priority of this complex (Sacks & Roy, 1982) when compared to other muscle groups of the leg. The results of Wickiewicz et al. (1984) found there was a proportionally greater loss of torque per unit change in velocity (above .41 radians per second) in the plantar flexors compared to the dorsiflexors, knee extensors and flexors. In the same study the plantar flexors lost 65% of their peak torque potential at an angular velocity of 2.1 radians per second, whereas the loss in torque potential for the dorsiflexors, knee extensors and knee flexors were 45%, 30%, and 20%, respectively.

Summary

Despite conflicting results, it seemed that the lower leg did make a significant contribution to vertical jumping (Bobbert & Van Ingen Schenau, 1988; Hubley & Wells, 1983; Luhtanen & Komi, 1978; Pandy & Zajac, 1991; Van Ingen Schenau, 1989). The goal of the proximal to distal movement pattern allowed for peak velocity differences to develop between segments, and allow for energy flow to maximize the effective energy of the body's center of mass at takeoff (Bobbert et al., 1986b; Bobbert & Van Ingen Schenau, 1988; Gregoire et al., 1984; Hudson, 1986; Pandy & Zajac, 1991; Pandy et al., 1990; Van Ingen Schenau, 1989; Van Soest et al., 1993). The tricep surae contributes to the vertical jump by means of muscle fiber shortening, transferring power from the knee to the ankle, and the catapult action of the Achilles tendon releasing stored elastic energy (Anderson & Pandy, 1993; Bobbert et al., 1986a; Bobbert et al., 1986b; Bobbert & Van Ingen Schenau, 1988; DeGraaf et al., 1987; Gregoire et al., 1984; Fukashiro et al., 1995; Hof et al., 1983; Pandy et al., 1990; Pandy & Zajac, 1991; Prilutsky & Zatiorsky, 1994; Van Ingen Schenau et al., 1985; Van Ingen Schenau et al., 1987; Zuurbier & Huijing, 1992). The muscle properties and architecture of the tricep surae indicated that force production was the primary goal (Sacks & Roy, 1982; Wickiewiczet al., 1984). All of the above aided plantar flexion of the ankle during jumping (Bobbert et al., 1986; Pandy & Zajac, 1991; Van Ingen Schenau, 1989).

CHAPTER 3

Methodology

This chapter details the procedures that were used to collect, analyze, and report the kinetic and kinematic data from vertical jumps. This chapter was divided into the following sections: (1) subjects, (2) equipment, (3) data collection and, (4) statistical procedures.

Subjects

The 30 subjects used in the study were 16 physically active males and 14 physically active females between the ages of 18 and 25 years. Physically active was defined as participation in a sport or activity that involves jumping, or participation in a training program that requires at least 20 minutes of aerobic activity. Either activity must be performed three times a week. The subjects were from Canada College and San Jose State University's gymnastic, basketball, volleyball, and softball teams. All subjects volunteered for the study via a flyer posted at San Francisco Bay area recreation departments and college athletic departments. Approval by the Human Subjects Institutional Review Board at San Jose State University and subject consent were obtained before data collection (Appendix A). Potential subjects were screened through the use of a participant information form (Appendix B) prior to participation in the study. Subjects with a history of lower body injuries that could hinder their performance of a maximal vertical jump were excluded from the study. Prior to data collection the subjects were assigned a number. Only the primary researcher had knowledge of the subject's name and number.

Equipment

The equipment used in this study were the Kistler type 9281B force plate interfaced with the Peak Performance Three Dimensional Motion Measurement System. Ground reaction forces under the foot were measured and sampled at 600 Hz. This was selected because the Peak Performance Technologies User's Reference Manual (1994) suggested that sampling rates be 10 times that of the operating speed of the video camera. Video taping of subjects was done with the Peak Performance Three Dimensional Motion Measurement System. A Panasonic D5000 video camera operating at 60 fields per second, was placed orthogonal to the sagittal plane of the subject (Hubley & Wells, 1983).

The space in which the vertical jumps took place was defined as the calibration frame. Digitizing the end points of a meter stick served to establish reference points as well as the calibration frame. The meter stick was videotaped prior to each subjects's performance of the three maximal vertical jumps.

The coordinates of anatomical landmarks defining the positions of the body segments were taken from the videotape via the Peak Performance Three Dimensional Motion Measurement System. The coordinates were properly scaled using a Butterworth filter (fourth order zero lag) (Bobbert & Van Ingen Schenau, 1990) and low-pass filtered at a cut-off frequency of 16 Hz.

Data Collection and Analysis

Subjects were instructed to remove all clothing and shoes except for black lycra shorts and black socks. The subject's height was measured in meters using a stadiometer, and the subject's weight was measured in kilograms using a counterbalance platform scale.

The anatomical landmarks identified on the subjects were the fifth metatarsophalangeal joint, joint center of the lateral malleolus, joint center of the lateral aspect of the knee, greater trochanter, and neck (at C5 level). A landmark on the center of the force plate served as a reference point for each video frame. The right side of the body was used to represent both sides as the vertical jump was assumed to be a bilaterally symmetric motion (Hubley & Wells, 1983). White colored adhesive discs identified the landmarks. A black three inch diameter circle was made with a surgical ink pen on the knee and neck landmarks prior to the placement of the white colored discs. The contrast in color made the white disc easier to see during the digitizing process. Landmarks were marked just prior to the time when the subjects were videotaped.

All subjects performed a five minute warm-up on a bicycle ergometer. The work load was one kp at 50 rpm. After completion of the warm-up the subjects were instructed on how to perform the vertical jump. The subjects were instructed to perform the jumps with the hands on the hips, the back straight to eliminate extraneous upperbody movement, and with a preparatory countermovement

(Gregoire et al., 1984). The subjects were then instructed to perform three submaximal practice jumps prior to the data collection in order to familiarize themselves with the jump style being utilized (Bobbert, Huijing, & Van Ingen Schenau, 1987). After the completion of the three practice jumps subjects were instructed to stand on the force plate and perform three maximum effort vertical jump trials. Data were gathered via video and force plate for each of the three maximum effort jump trials. Any of the three maximal jump trials deviating from the set guidelines was not used for analysis. The maximal vertical jump providing the longest time in the air, as calculated by the force plate, was the trial to be analyzed. Subjects were assigned to groups based upon the height of their jump. Those subjects with the top ten highest jumps were assigned to the high group. Those subjects with next ten highest jumps were assigned to the average group. The remaining subjects were assigned to the low group.

Measurements of the distance between the head of the fifth metatarsalphalangeal to the lateral malleolus were calculated by the Peak Performance Three Dimensional Motion Measurement System. Mass of the foot was calculated by multiplying the subject's body mass by .0145, which was the mass fraction of the foot segment (Winter, 1990).

The mass moment of inertia of the foot segment was calculated by multiplying the mass of the segment by the radius of gyration squared. The radius of gyration was determined by multiplying the length of the limb segment and the limb center of gravity. The center of gravity of the foot segment was calculated according to Winter (1990).

The landmarks were digitized beginning at the start of the jump countermovement to the point upon which the subject reached the apex of his jump. The Peak Performance Three Dimensional Motion Measurement System calculated both angular and linear displacements, velocities, and accelerations of the foot, as well as the coordinates of the center of mass of the foot. Net vertical jump displacement was determined by calculating the greatest vertical distance between the highest position attained by the landmark on the greater trochanter and the landmark on the force plate (Van Soest et al., 1985). Ground reaction forces in the vertical and horizontal directions as well as the point of application of these forces were recorded by the force plate (Van Soest et al., 1985). The Peak Performance Three Dimensional Motion Measurement System synchronized the kinetic and kinematic data. The kinematic data were used in conjunction with the kinetic data calculated from the forceplate to create a free body diagram of the foot (Appendix C). Using inverse dynamics and basic linked segment equations (Winter, 1990), ankle reaction forces, ankle moments, and ankle power were calculated for the three groups of subjects. Power output about the ankle joint was determined by multiplying the net ankle moments by the angular ankle velocities (Winter, 1990). Mean ankle power, mean ankle torque and mean ankle angular velocity values were determined by summing the respective values that were calculated for each video field during the vertical jump push-off phase, and then dividing the sum by the number of video fields that had elapsed during the push-off phase of the vertical jump. Total ankle power was determined by summing the ankle power values that were calculated for each video field during the vertical jump push-off phase.

Statistical Procedures

The reliability of the researcher's digitizing technique was determined by digitizing an object of known length. The object used was a meter stick. Fifteen frames were digitized on two separate days and then statistically analyzed using a Pearson Product Moment Correlation and a one way analysis of variance.

The overall means and standard deviations were calculated using SPSSX software, and were reported for the following variables: age, weight, and height. The means and standard deviations for jump height, ankle power, peak ankle power, total ankle power, ankle torque, peak ankle torque, angular ankle velocity, peak angular ankle velocity, minimum ankle angle at push-off, and maximum ankle angle at push-off were reported as they pertained to each of the three jump groups.

Pearson product-moment correlations were calculated to see if any significant relationships existed between vertical jump height and the following ankle variables: total power, mean power, peak power, mean torque, peak torque, mean angular velocity, peak angular velocity, minimum angle during push-off, and maximum angle during push-off. Additional Pearson product-moment correlations were calculated for ankle power and the variables of mean torque and mean angular velocity. The level of significance for the correlations was set at .05 (Van Soest et al., 1985). A coefficient of determination was calculated for all significant correlations.

One-way analyses of covariance were used to eliminate the effects of body weight and to compare differences between total ankle power, mean ankle power, peak ankle power, mean ankle torque, and peak ankle torque for the three groups. The alpha level was set at .05 (Van Soest et al., 1985). Tukey post hoc tests were used as follow-up procedures when significant main effects were found in the one way analysis of covariance. All statistical calculations were performed using SPSSX software.

CHAPTER 4

Results and Discussion

Results

Utilizing the methods described in the previous chapter, kinetic and kinematic data were collected on each subject's highest vertical jump. All variables were calculated from the start of the push-off phase until takeoff. The chapter is arranged in the following sections: (1) subjects and jump height, (2) digitizing accuracy, (3) ankle power, (4) ankle torque, (5) angular ankle velocity (6) ankle angles, (7) discussion, and (8) summary.

Subjects and Jump Height

The means and standard deviations of the 30 subjects for age, height, and weight were 21.1 ± 2.2 years, 1.7 ± .1 meters, and 72.3 ± 12.7 kilograms, respectively. Mean jump height for the 30 subjects was .50 ± .09 m (meters). The mean jump heights for the high, average, and low groups were .61 ± .07 m, .49 ± .02 m, and .41 ± .05 m, respectively (Appendix D). Statistically significant differences in jump height were found between the high group and the average and low groups. Statistically significant differences were also found between the average group and the low group for jump height.

Digitizing Accuracy

Three Pearson product-moment correlations were performed to assess the relationship between the distance calculated between the end points of a meter digitized on two different days, and the actual length of the meter stick. The correlations were as follows: between day one calculated distances and day two calculated distances, day one calculated distances and the actual meter stick length, day two calculated distances and the actual meter stick length. The three correlations revealed a strong relationship (r= .98) between the digitized meter stick distance and the actual meter stick length. The one way analysis of variance, with an alpha level of .05, revealed no differences between the digitizing done on different days and the actual meter stick length.

Ankle Power

Mean ankle power for the 30 subjects was 309 ± 211 W. The mean ankle power production for the high, average, and low groups was 499 ± 248 W, 186 ± 62 W, and 243 ± 130 W, respectively. Statistically significant differences in mean ankle power were found between the high group and the average group, and the high group and the low group. Mean time history for ankle power production is presented in figure 1. The correlation coefficient between vertical jump height and ankle power production was .701 for the 30 subjects.

Mean peak ankle power for the 30 subjects was 967 ± 422 W. The high, average, and low groups had peak ankle power of 1282 ± 495 W, 886 ± 237 W, and 733 ± 307 W, respectively. No statistically significant differences were found between groups. The correlation between jump height and peak ankle power was .766 for the 30 subjects.

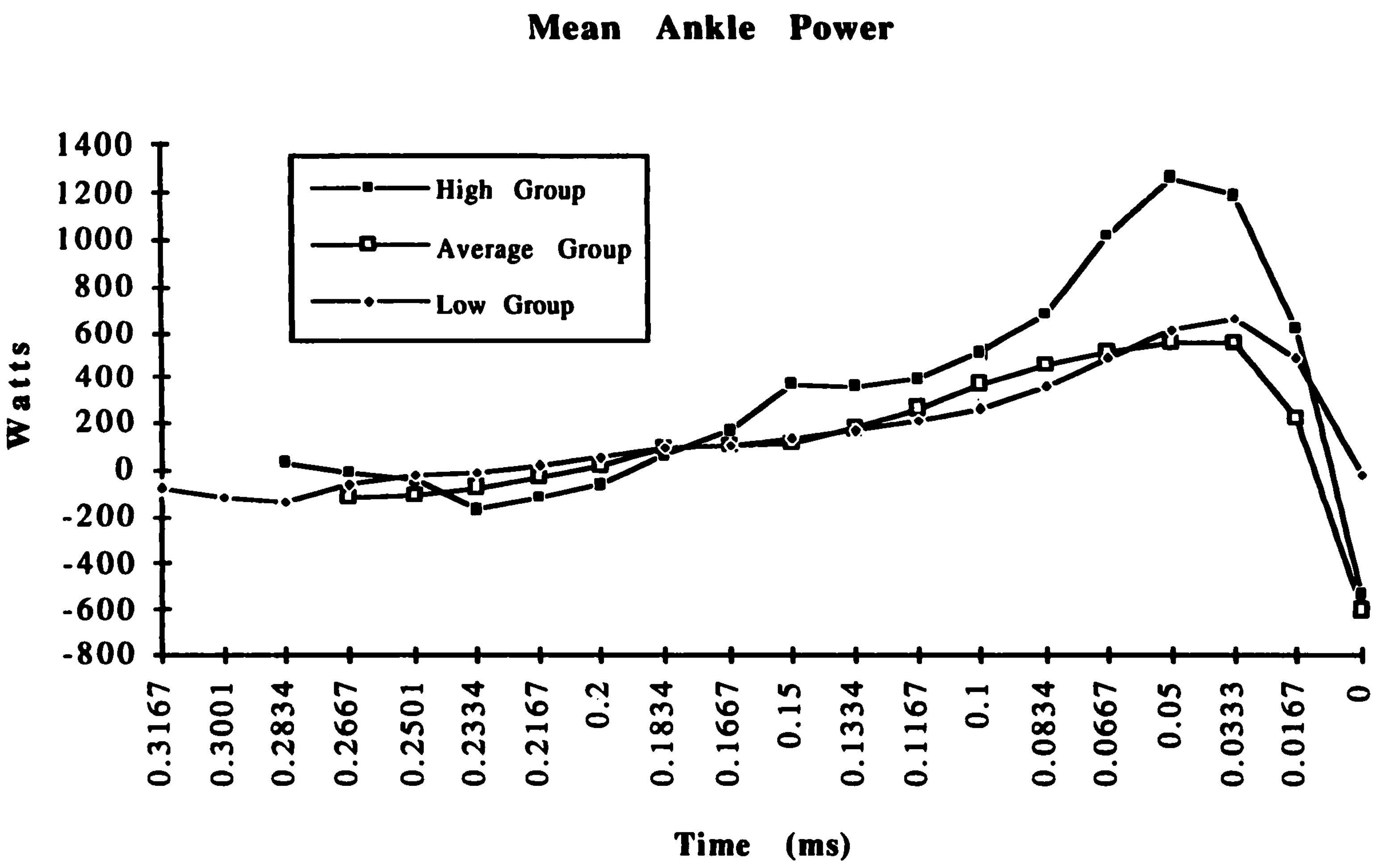

Figure 1. Mean ankle power produced during the push-off phase of a vertical jump. Note: one way analysis of covariance indicated significant differences ($F = 6.95$, $p > .004$). Tukey post hoc revealed the high group had significantly higher mean values than the average and low groups ($p < .05$).

Mean total ankle power was 3962 ± 2160 W for the 30 subjects. Values of 5894 ± 2493 W, 2769 ± 1119 W, 3223± 1113 W, were produced by the high, average, and low groups, respectively. Statistically significant differences were found between the high group and the average group, and between the high group and the low group. The graph for mean total power is presented in figure 2. The correlation coefficient between jump height and total ankle power was .677 for the 30 subjects.

Ankle Torque

The mean ankle torque was 147 ± 65 Nm for the 30 subjects. Mean ankle torques for the high, average, and low groups were 197 ± 72 Nm, 137 ± 35 Nm, and 107 ± 49 Nm, respectively. Differences in mean ankle torque were found to be statistically significant between the high group and the average and low groups. Additionally, significant differences were found between the average and low groups. The mean time history for mean ankle torque is presented in figure 3. A correlation coefficient of .772 was calculated between jump height and ankle torque for the 30 subjects.

Peak torque for all subjects was 204 ± 93 Nm. Peak torques for the high, average, and low groups were 274 ± 114 Nm, 200 ± 45 Nm, and 139 ± 54 Nm, respectively. Peak torque differences were found to be statistically significant between the high group and the average and low groups. Significant differences were also present between the average group and the low group. The graph of peak ankle torque is presented in figure 4. A correlation coefficient of .739 was

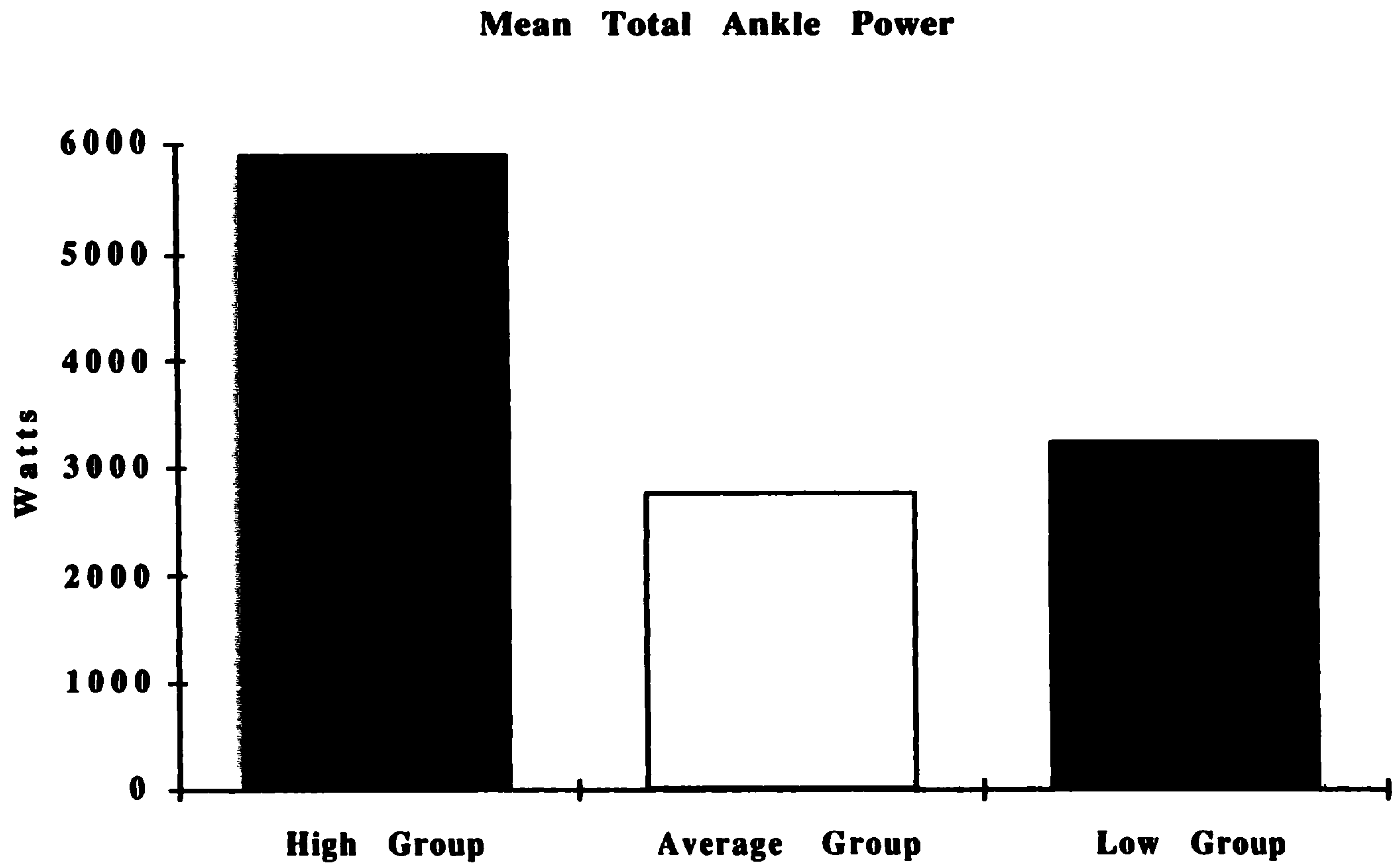

Figure 2. Mean total ankle power produced during the push-off phase of a vertical jump.

Note: one way analysis of variance revealed significant differences ($F = 6.60$, $p > .005$). Tukey post hoc revealed the high group had significantly higher mean values than the average and low groups ($p < .05$).

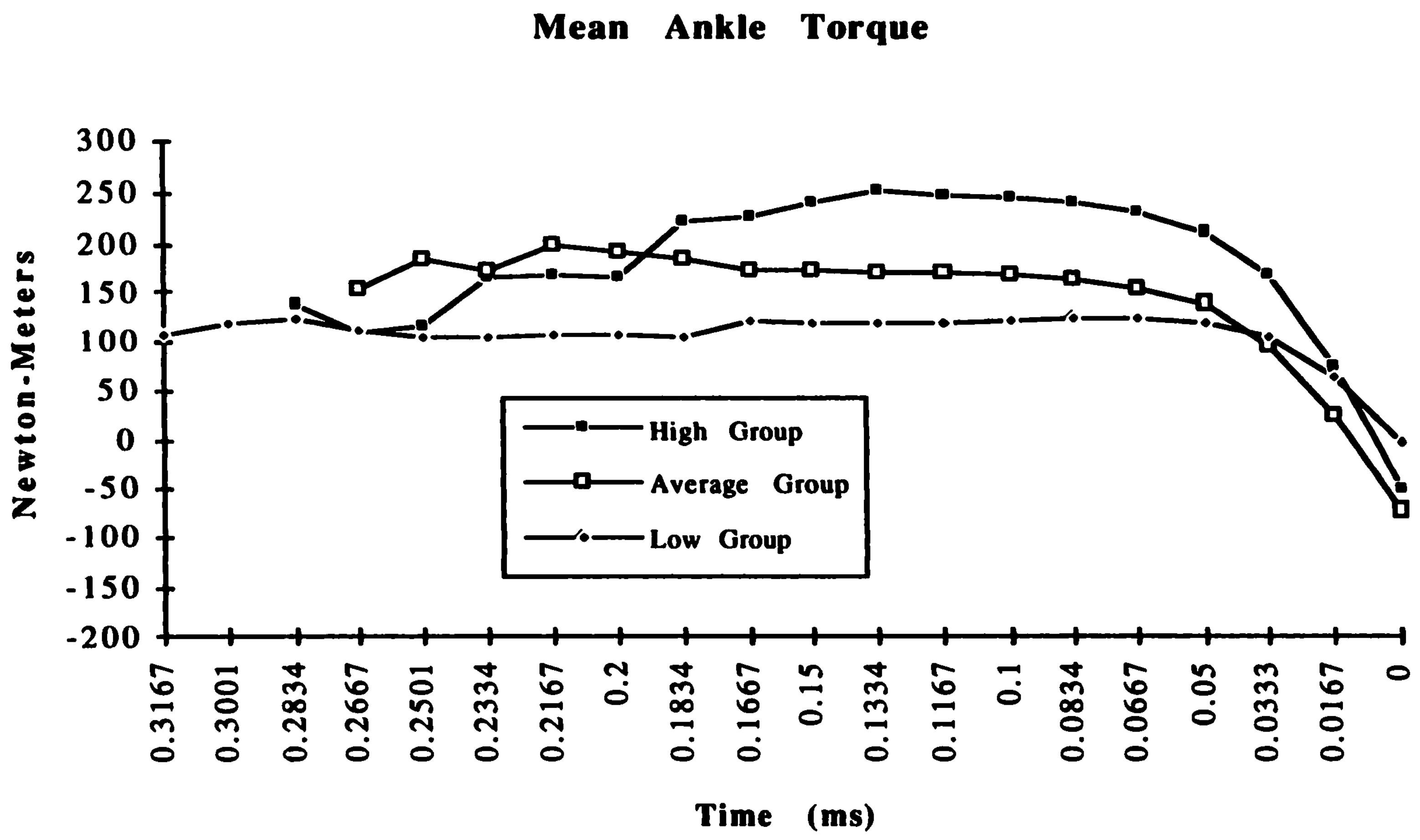

Figure 3. Mean torque produced about the ankle during the push-off phase of a vertical jump.

Note: one way analysis of covariance indicated significant differences (*F* = 4.12, *p* > .028). Tukey post hoc revealed the high group had significantly higher mean values than the average and low groups, and the average group had significantly higher mean values than the low group (*p* < .05)

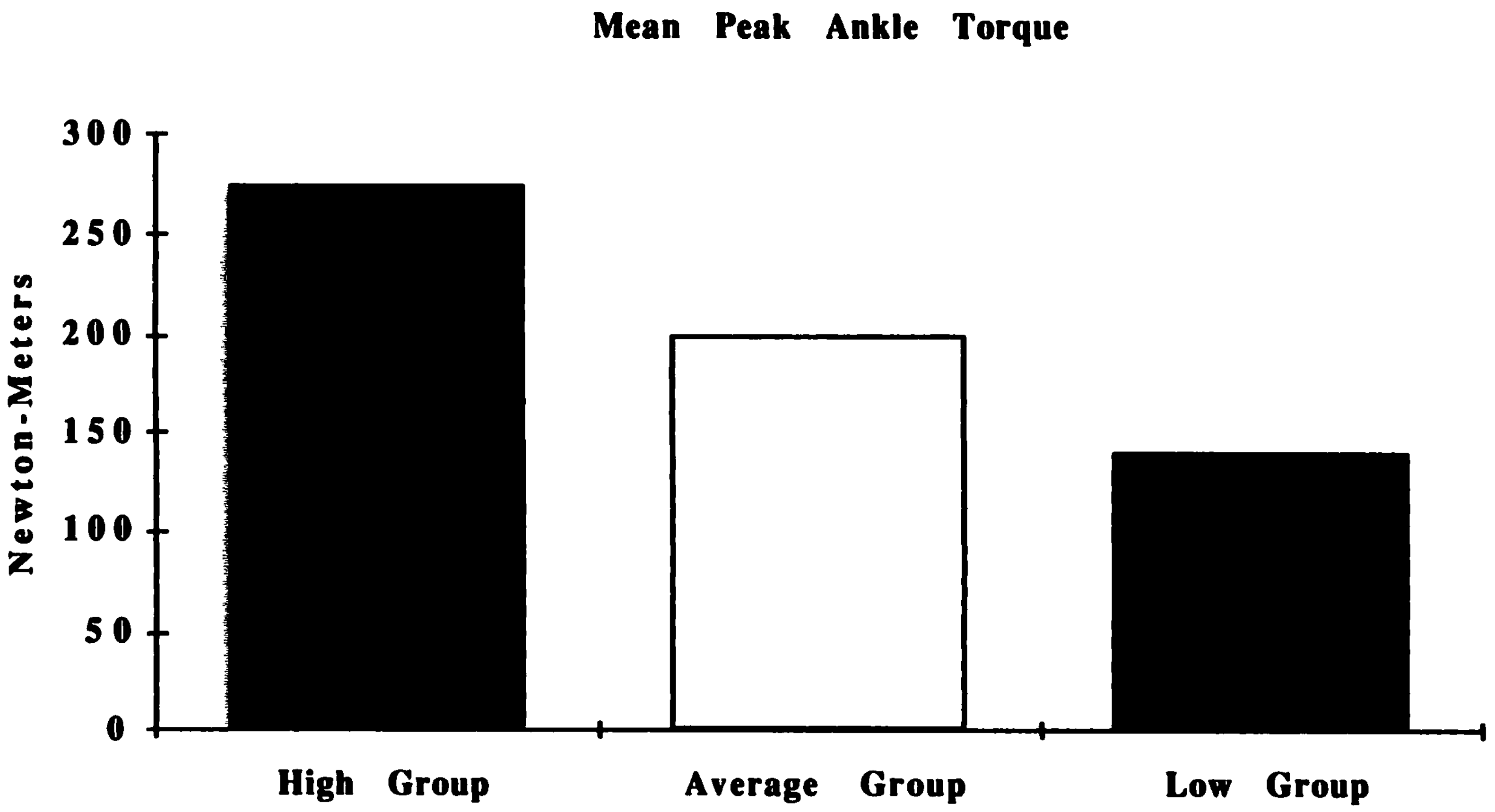

Figure 4. Mean peak ankle torque produced during the push-off phase of a vertical jump.

Note: one way analysis of covariance revealed significant differences ($F = 4.51$, $p > .061$). Tukey post hoc revealed the high group had significantly higher mean values than the average and low groups, and the average group had significantly higher mean values than the low group ($p < .05$).

calculated between jump height and peak ankle torque for the 30 subjects.

Angular Ankle Velocity

Mean angular velocity of the ankle was 3.3 ± 1.0 radians per second for the 30 subjects. Velocity values for the high, average, and low groups were 3.7 ± 0.8 radians per second, 3.0 ± 0.9 radians per second, and 3.2 ± 1.3 radians per second, respectively. No statistically significant differences were found between the groups. A correlation coefficient of .135 was calculated between angular velocity and jump height.

Peak angular velocity for the 30 subjects was 9.8 ± 2.2 radians per second. Peak angular velocities for the high, average, and low groups were 9.7 ± 2.0 radians per second, 10.3 ± 2.9 radians per second, and 9.5 ± 1.6 radians per second, respectively. No statistically significant differences were found between the groups. The correlation between peak angular velocity and jump height was .004.

Ankle Angles

Mean minimum ankle angle for the 30 subjects was 1.6 ± .1 radian. Ankle angles for the high, average, and low groups were 1.6 ± .2 radian, 1.6 ± .2 radian, and 1.6 ± .2 radian. No significant differences were found. The correlation coefficient between jump height and minimum ankle angle was -.11.

Mean maximum ankle angle for the 30 subjects was 2.4 ± .1 radian. Values for the high, average, and low groups were 2.4 ± .1 radian, 2.4 ± .1 radian, and 2.4 ± .1 radian, respectively. No significant differences were found. The correlation coefficient between jump height and maximum ankle angle was -.14.

Discussion

Previously reported values for mean power about the ankle were 298 W and 343 W by Bobbert et al. (1986) and Van Soest et al. (1985), respectively. These values compared favorably to the mean ankle power of 309 W for the 30 subjects in this study.

The correlation coefficient between mean ankle power and vertical jump height was .70 ($p<.05$). The calculation of the coefficient of determination indicated that approximately 50% of the variance in vertical jump height can be accounted for by mean ankle power. Only the high group was found to be statistically significantly different compared to the average and low groups in the production of ankle power. The mean values of ankle power production and total ankle power production were higher in the low group than in the average group. As the differences between the average and low groups for these variables were not found to be statistically significant, the differences present can be attributed to random chance. Therefore, a greater mean ankle power production and greater total ankle power production will be required to be a more successful jumper.

Previous values for peak ankle power reported by De Graaf et al. (1987), Van Soest et al. (1985), Van Ingen Schenau et al. (1985), Bobbert et al. (1986), and Bobbert et al. (1987) were 1404 W, 1218 W, 1250 W, 943 W, and 1225 W, respectively. Most of these values were higher than the 967 W that was calculated in this study for all

30 subjects. The probable explanation for this was that the participants in the previous studies were all well trained athletes. The peak ankle power for the high group in the present study was 1282 W. In the present study the high group could be considered similar to the well trained athletes of the previous studies. As a result the peak ankle power value for the high group was comparable to the previously reported values, which belonged to the well trained athletes. The correlation between jump height and peak power was .77 ($p<.05$). The calculated coefficient of determination demonstrated that peak power accounted for approximately 60% of the variance in jump height. There were no previously reported values for total power. The correlation coefficient between jump height and total power was .68 ($p<.05$). Statistically significant differences in mean total power were found between the high group and the average and low groups. The data from this study indicated that for a jumper to be more effective, his production of total ankle power must be higher and he must maintain a higher amount of mean ankle power. A significant correlation coefficient for peak power about the ankle was calculated. Therefore, attaining a high peak ankle power could be beneficial to jumping higher, though no statistically significant differences were found.

Previous studies by Van Soest et al. (1985), Bobbbert et al. (1986), Bobbert et al. (1987), and Van Ingen Schenau (1985) reported mean ankle torque values of 117 Nm, 102 Nm, 132 Nm, and 155 Nm, respectively. The values calculated for the low and average groups (107 Nm and 137 Nm, respectively) were similar to the previously reported data. The 197 Nm from the high group was greater than the previously reported values for mean ankle torque, which seems logical as the mean jump height for the high group was higher than the mean jump height for the highly trained subjects in the previous studies. Of the variables correlated to jump height, mean torque had the strongest relationship, with a correlation coefficient of .77. Sixty percent of the variation in jump height can be attributed to mean ankle torque, as determined by the calculation of the coefficient of determination. Statistically significant differences in mean ankle torque were found between the high group and the average and low groups, and between the average group and the low group.

Earlier studies by Van Ingen Schenau et al. (1985), De Graaf et al. (1987), Van Soest et al. (1985), Bobbert et al. (1986), and Bobbert et al. (1987) reported peak torque values of 150 Nm, 194 Nm, 153 Nm, 133 Nm, and 155 Nm, respectively. Values for the high and average groups were 274 Nm and 200 Nm, respectively. The higher torque value reported for the high group was greater than what was found in previous studies. This was due to the high group having a greater vertical jump than subjects participating in previous studies. The peak torque value for the average group was higher than previously reported values but reasonably close to the 194 Nm reported by De Graaf et al. (1987). The low group's value of 139 Nm was comparable to the previous data. Peak torque had a correlation coefficient of .74 ($p<.05$) with jump height. Fifty-five percent of the variation in jump height can be attributed to peak torque as determined by the calculation of the coefficient of determination. Statistically significant differences in peak torque were found between the high group and the average and low groups, and between the average group and the low group.

The correlation coefficients between vertical jump height and the variables of mean angular velocity, peak angular velocity, minimum ankle angle, and maximum ankle angle were all approximately .13 or less ($p>.05$). Furthermore, there were no significant differences found between any of the groups for these variables. This study found torque to have the greatest influence on vertical jump height, which demonstrates that jump height was dependent on the ability to produce high peak torques and high mean torques.

The strongest relationship was found to be between mean power and mean torque ($r=.84$). The coefficient of determination revealed that mean torque accounted for over 70% of the variation in mean ankle power. A lower but still significant correlation coefficient of .45 was found between mean power and mean angular velocity. These correlations were logical since power was the product of torque and angular velocity. Yet, as already mentioned above the angular velocity was not found to be statistically different in the three groups, whereas the torque was. Based on the findings of the present study, a high vertical jump requires production of a high mean ankle torque and a high peak ankle torque.

Although the effects of bodyweight were eliminated by performing a one-way analysis of covariance, the effects of the subjects' body composition were not eliminated. As a result body composition may have affected the height achieved in the vertical jump as well as the variables of mean torque, peak torque, mean power, peak power, and total power. Subjects were both male and female in this study. The low group was largely comprised of females, but the average group had an equal and even distribution of males and females. One female was in the high group. The subjects with a greater amount of lean body mass would theoretically have more working muscle in the legs to aid in vertical jumping (assuming that the distribution of fat throughout the body is relatively uniform). Females generally have a greater percentage of body fat than men and therefore could be at a disadvantage when vertical jumping.

The findings of previous studies substantiated the findings of the present study. Van Soest et al. (1993) found the gastrocnemius further contributed to power production by contracting at a relatively low velocity. According to the force velocity relationship (Brooks & Fahey, 1985), at a lower velocity of contraction a muscle generated more force. Van Soest et al. (1993) reported at low velocities the biarticular gastrocnemius delivered high forces, and without the gastrocnemius, high torques and high velocities would not occur in the ankle joint. The monoarticular muscles of the legs produce power at high velocities while the biarticular leg muscles add to power production at low velocities (Van Soest et al., 1993).

Zuurbier and Huijing (1992) attributed some of the gastrocnemius contraction velocity to the release of energy from the Achillies tendon. This way one can have a higher speed of contraction accompanied by higher torques. Bobbert et al. (1986a) found the compliancy of the tendon crossing the ankle to be well suited for combining a high angular velocity with a plantar flexion moment of about 80 Nm during the last part of the push-off phase.

Wickiewicz et al. (1984) found a greater loss of torque with increase in velocity in the plantar flexors than in the other muscles of the leg. Wickiewicz et al. (1984) concluded that plantar flexors should have the greatest potential for force production compared to the other muscles in the leg because its fibers are arranged in parallel. The parallel arrangement is suited for force production, not speed production, which would require the fibers to be in a series arrangement. Sacks and Roy (1982) also found the architecture of the plantar flexors to be more suited to force production than the other leg muscles.

Contrary to the findings of the present study, Bangerter (1967) concluded that the plantar flexors did not contribute significantly to vertical jumping. Miller and East (1976) also found the contribution of the plantar flexors to be low. The percent contributions for the four subjects in the Miller and East (1976) study were 5%, 4.7%, 7.2%, and 4.4%, respectively. The percent contributions of the plantar flexors in studies by Hubley and Wells (1983), and Luhtanen and Komi (1978) were higher, 23% and 22%, respectively. Luhtanen and Komi (1978) concluded that the plantar flexors made an important contribution in maximal vertical jumping. Although the studies of Hubley and Wells (1983) and Luhtanen and Komi (1978) determined similar lower leg contributions to jumping, several points must be considered. Hubley and Wells (1983) had the subjects perform jumps without the use of their arms and were studying the legs only. While Luhtanen and Komi (1978) were studying all the body segments and allowed arm swing during the jumps. Therefore, the lower leg contribution obtained by Wells and Hubley (1983) would have been smaller had the upper body segments been included in the calculations. Wells and Hubley (1983) felt the isolation technique used by Luhtanen and Komi (1978), which lacks the synergy and segmental coordination found in a vertical jump, may have affected the validity of the study. Hubley and Wells (1983) stated that the segmental technique used by Luhtanen and Komi (1978) and Miller and East (1976) was influenced by the mass of the individual body segments. Based on that observation, small body segments would appear to make a smaller contribution to the vertical jump.

Summary

The results of this study found the highest jumpers produced greater values for the following variables: mean power, peak power, total power, mean torque, and peak torque (table 1). The highest

Table 1

Summary of Ankle Variables During Vertical Jump

	High group		Average group		Low group		F	F
	Mean	SD	Mean	SD	Mean	SD	Value	Probability
Jump Height (M)	0.61	0.07	0.49	0.02	0.41	0.05		
Mean Power (W)	499.0	248.0[1]	186.0	622.0	243.0	130.0	6.95	.004*
Peak Power (W)	1282.0	495.0	886.0	237.0	733.0	307.0	3.11	.061
Total Power (W)	5894.0	2493.0[1]	2769.0	1119.0	3223.0	1113.0	6.60	.005*
Mean Torque (Nm)	197.0	72.0[1]	137.0	35.0[2]	107.0	49.0	4.12	.028*
Peak Torque (Nm)	274.0	114.0[1]	200.0	45.0[2]	139.0	54.0	4.51	.061*
Mean Ang. Vel.	3.7	0.8	3.0	0.9	3.2	1.3	1.16	.330
Peak Ang. Vel. (Rad/s)	9.7	2.0	10.3	2.9	9.5	1.6	.451	.642
Min. Angle (Rad)	1.6	0.2	1.6	0.2	1.6	0.2	.223	.798
Max Angle (Rad)	2.4	0.1	2.4	0.1	2.4	0.1	.074	.983

*Note. Significant statistical difference ($p<.05$)

[1] Tukey post hoc revealed high group had significantly higher mean values than average and low groups.

[2] Tukey post hoc revealed average group had significantly higher mean values than the low group.

torque values were responsible for producing the greater jump height and greater power values. The physiological architecture of the lower leg, with its muscle fibers in parallel arrangement, is suited for the production of force, hence torque, and not speed (Wickiewicz et al., 1984). The Achillies tendon contributed to the contraction velocity of the gastrocnemius through the release of stored elastic energy (Zuurbier & Huijing, 1992). Therefore, the role of the lower leg musculature in jumping was to produce torque, while the released energy stored in the Achilles tendon contributed to speed of contraction.

CHAPTER 5

Summary and Recommendations

Statement of the Problem

In many sports the ability to vertically jump a great distance is a highly desirable skill. In hopes of improving our methods of training for vertical jumping, athletes need to know the lower body contributions to vertical jumping, and then develop specific training protocols based on these joint contributions and characteristics. Only a few investigations have looked at lower body contributions to vertical jumping. These studies did not explore how joint contribution, specifically the lower leg, varied amongst jumpers of different abilities. The goal of the present study was to characterize the behavior of the lower leg as well as determine its importance in vertical jumping.

Methods

Thirty female and male college-aged athletes performed three maximal vertical jumps on a Kistler 9281 B force plate while being videotaped at a right angle with a Panasonic D5100 video camera operating at 60 fields per second. The videotapes were digitized and kinematic data were calculated by the Peak Performance Three Dimensional Motion Measurement System. The subjects achieving the ten highest vertical jump distances were assigned to the high group. The next ten highest scorers were placed in the average group. The final ten jumpers were placed in the low group. The kinematic data were used in conjunction with the kinetic data calculated from the force plate to create a free body diagram of the foot (Appendix C). Using inverse dynamics, the ankle reaction forces, moments, and power were calculated for the three groups of subjects. Pearson product-moment correlations were performed to determine relationships between the calculated kinematic and kinetic variables and vertical jump height. One-way analyses of covariance were used to eliminate the effects of body weight and to compare differences between total ankle power, mean ankle power, peak ankle power, mean ankle torque, and peak ankle torque for the three groups. The alpha level was set at .05 (Van Soest et al., 1985). Tukey post hoc tests were used as follow-up procedures when significant main effects were found in the one way analysis of covariance. All statistical calculations were performed using SPSSX software.

Results and Conclusions

Significant relationships were found between jump height and the variables of mean power, peak power, total power, mean torque, and peak torque. Additional significant relationships were found between mean power and mean torque, and mean power and mean angular velocity. The high group had significantly greater mean power, total power, mean torque, and peak torque than the average and low groups. The average group had significantly greater mean torque and peak torque than the low group.

The results of this study determined that the lower leg had a significant role in determining vertical jump height. In order to be an above average jumper one would have to generate a higher peak ankle power and total ankle power in addition to maintaining a higher mean ankle power through out the push-off phase of the jump. Additionally, torque was found to have had the most important role in affecting jump height as well as affecting ankle power production.

This study found that jump height and ankle power increased due to increases in ankle torque rather than in angular velocity. These characteristics were consistent with the findings of Sachs and Roy (1982), Van Soest et al. (1993), Wickiewicz et al. (1984), and Zuurbier and Huijing (1992), that the lower leg physiology was suited for force production, not velocity.

Based on these findings, it was concluded that an appropriate training protocol would be to improve the force production capabilities and thus the torque production of the lower leg by way of performing plantar flexion against a heavy resistance. Heel raises and seated heel raises would satisfy this requirement (Yessis & Hatfield, 1986). The use of frontal platform shoes to overload the lower leg would also be recommended based upon the findings of this study (Yessis & Hatfield, 1986). One may also wish to spend time stretching the Achilles tendon to enhance the tendon's compliance, which would potentially allow for greater transfer of stored elastic energy, thus contributing to a higher jump (Anderson & Pandy, 1993). Plyometric activities in frontal platform shoes would also be recommended. The result would be a greater torque developed in response to the higher impact forces of landing (Yessis & Hatfield, 1986), body weight being on the ball of the foot due to the frontal platform shoes, and an increased stretch of the Achilles tendon due to the heel being able to drop to a position below parallel. Additionally the myotatic stretch reflex time would be minimized (Yessis & Hatfield, 1986).

Recommendations

Based on the present investigation the following issues should be addressed in future research studies.

1. The relative contributions made by the hip, knee, and ankle joints should be studied among jumpers of differing abilities.
2. Future studies on vertical jumping should be designed with a practical intent so that the results can be applied to an athlete's training program. Much of the past research has focused on the biomechanical mechanisms involved in jumping, but not on ways to improve jumping ability or jump training protocols.
3. When grouping jumpers of varying ability it is advisable that the groups have at least a ten centimeter difference between them. This will create a greater spread in the data.

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APPENDIX A

SJSU SAN JOSE STATE UNIVERSITY

A campus of The California State University

College of Applied Sciences and Arts • *Department of Human Performance*
One Washington Square • San José, California 95192-0054 • 408/924-3010 • FAX 408/924-3053

Agreement to Participate in Research

Responsible Investigator:_Bryan McCoy_______________________

Title of Protocol: Role Of The Lower Leg In Determining Vertical Jump Height.

Subject:____

I have been asked to participate in a research study investigating lower leg involvement in vertical jumping. I will be asked to wear lycra shorts and socks, and have my fifth toe, ankle, knee, hip, and neck joints marked with a surgical pen and adhesive dots while being videotaped vertically jumping on a forceplate. My risk of injury is no greater than the risks of every day normal activity. Possible injuries may include stubbbed toe, sprained ankle, bruised heel, or falling due to loss of balance upon landing from jump. I understand that no direct benefits to myself are expected. I understand that the results of this study may be published but no information identifying me will be included without my authorization. Questions concerning this study may be addressed to the principal researcher, Bryan K. McCoy (415-599-3352). Complaints about this study may be presented to the Human Performance Chair (James Bryant, 408-924-3010). Questions or complaints about research, subject's rights, or research related to injury may be presented to Serena Stanford, Ph.D., Associate Vice President of Graduate Studies and Research, at (408) 924-2480. My consent is given voluntarily without being coerced. I may refuse to participate in this study or in any part of this study, and I may withdraw at any time, without prejudice to my relations with SJSU. I acknowledge that I have received a signed and dated copy of the consent form.

*The signature of a subject on this document indicates agreement to participate in the study.

*The signature of a researcher on this document indicates agreement to include the above named subject in the research and attestation that the subject has been fully informed of his or her rights.

______________________ ______________
Subject's Signature Date

______________________ ______________
Investigator's Signature Date

APPENDIX B

SJSU SAN JOSE STATE UNIVERSITY

A campus of The California State University

College of Applied Sciences and Arts • Department of Human Performance
One Washington Square • San José, California 95192-0054 • 408/924-3010 • FAX 408/924-3053

Potential Subject Information Sheet

Name ____________________ Date ____________

Home Phone Number ______________

Age ________

Have you ever suffered INJURY to the lower extremity (hips to toes) such as broken bones, torn ligaments, torn muscles, or ruptured tendons that would limit the use of your legs in performing a maximal effort vertical jump?

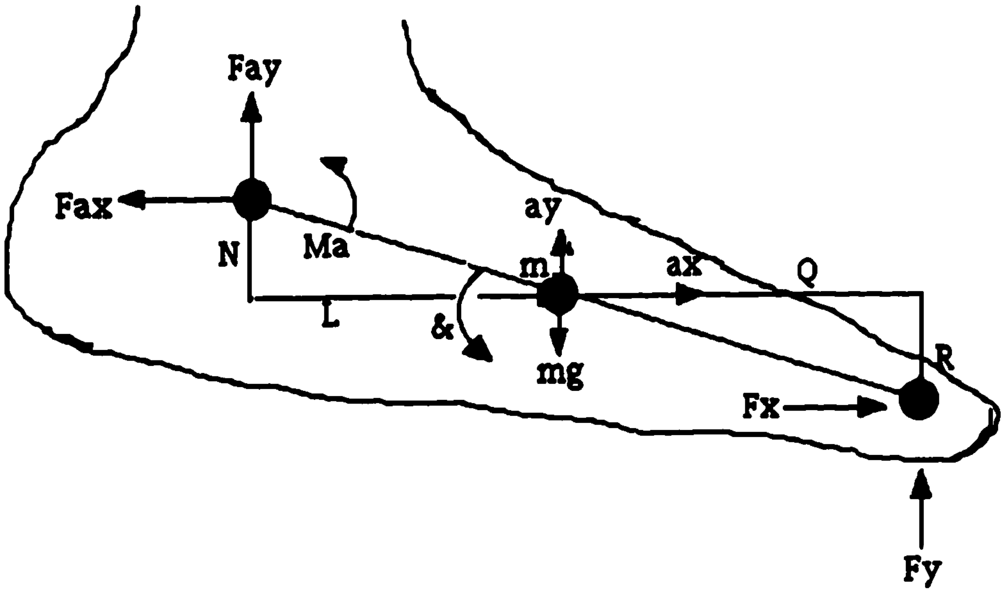
Yes No

Does your physical activity consist of a minimum of 20 minutes of aerobic training at least three times a week or are you a participant in a sport that involves jumping, such as basketball, volleyball, track and field, at least three times per week.

Yes No

APPENDIX C

Free Body Diagram of the Foot



Fax = Max - Fx
Fay = May - Fy = mg
M= I&
Ma = (Fx * R) + (Fy * Q) - (Fay * L) - (Fax * N) = I&
Ma = -(Fx * R) - (Fy * Q) + (Fay * L) + (Fax * N) + I&

Fax, Fay = joint reaction force
Ma = moment of the joint
Fx, Fy = ground reaction force
ax, ay = acceleration of the center of segment
m = segment mass
g = gravity due to acceleration
I = inertia moment of the segment
& = angular acceleration of the segment
L, N, Q, R = distance

Adapted from Fukashiro & Komi (1987)

APPENDIX D

Demographics Table of Subjects

	Number of Males	Number of Females	Age (Yrs.)		Weight (Kg.)		Height (Meters)		Jump Height (Meters)	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
High Group Males	9.0	- -	21.6	2.1	79.8	10.6	1.8	0.1	.62	.06
High Group Females	- -	1.0	22.0	--	73.4	--	1.8	--	.52	--
Average Group Males	5.0	- -	20.8	3.0	71.9	16.8	1.8	0.2	.49	.02
Average Group Females	- -	5.0	20.4	1.1	72.4	7.3	1.7	0.1	.49	.02
Low Group Males	2.0	- -	24.0	1.4	88.2	1.4	1.8	--	.47	--
Low Group Females	- -	8.0	20.4	2.2	62.8	10.2	1.6	0.1	.41	.05