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An investigation of the relationship between impact force attenuation in landing and isokinetic strength of knee muscles in individuals with different training backgrounds

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University of Tennessee - Knoxville

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To the Graduate Council:

I am submitting herewith a thesis written by Jeremy Adam Steeves entitled "An investigation of the relationship between impact force attenuation in landing and isokinetic strength of knee muscles in individuals with different training backgrounds." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Exercise Science.

Songning Zhang, Major Professor

We have read this thesis and recommend its acceptance:

Clare E. Milner, Eugene Fitzhugh

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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An Investigation of the Relationship between Impact Force Attenuation in Landing and Isokinetic Strength of Knee Muscles in Individuals with Different Training Backgrounds

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Jeremy Adam Steeves

December, 2008

Dedication

I would like to dedicate the thesis to my parents Cliff and Kathy, and my sisters Kelsey, Sarah and Jana and my girlfriend Betsy Anderson. Day by day in every way I aim to be better and better to make you all proud. Your unfailing love, patience, guidance and support throughout life’s journey and during this process has driven me to succeed.

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Many people have mentored and helped to guide me through this process, providing their advice, feedback, support and criticism. Primarily, I would like to thank my advisor, Dr. Songning Zhang, for his support, patience and guidance during this research experience. I would also like to thank my committee members, Dr. Clare Milner, and Dr. Eugene Fitzhugh for their feedback, input and corrections. Thank you all for your understanding and accommodation with regards to working around my other goals and dreams. Mike Wortley, Julia Freedman, Stacy Hunter, John Dean, Duncan Simpson and Brian Tyo, I would be remiss if I did not thank you for your assistance during data collection and your counsel any time I had a question or problem.

Abstract

Skeletal muscle is a major active mechanism of impact force attenuation in human movement. During the landing phase impact attenuation is achieved through eccentric contraction of the muscles of the lower extremity. However, few studies have investigated the effects of knee strength, especially eccentric strength, on impact attenuation during landing. Therefore the relationship was assessed in fourteen healthy, male volunteers. Seven NCAA Division I College football players (TRAINED) and seven recreationally active university students with limited sport training or competitive sport background (REC) participated in two testing sessions. Isokinetic testing of the knee extensor and flexor muscles was performed concentrically at 60 and 180 degree·sec^{-1}, and eccentrically at 60 degree·sec^{-1}. 3D kinematic and ground reaction force (GRF) data were collected during drop landings from heights of 40, 60cm and 100% of each individuals maximum jump height. The TRAINED had greater concentric strength, vertical jump height, but no significant differences existed in the eccentric strength (336 vs 340 N.m/kg) between the groups. The TRAINED had marginally greater peak GRFs (2.7 & 3.5 BW vs 2.0 & 2.7 BW for 40 and 60 cm, $p=0.051$) and significantly less time to the peak (0.048 & 0.043 s vs 0.060 & 0.053) compared to the REC in drop landing. The TRAINED used less but non-significant knee flexion range of motion (-60.7 & -54.1 degree vs -62.7 & -69.6 degree) during drop landing than the REC. There were high, positive and significant correlations between the peak eccentric knee extensor torque and time to the first and second peak GRF. Despite all their training the results did not find any significant differences in eccentric strength of the TRAINED subjects in comparison to their REC counterparts. The TRAINED subjects adopted a stiffer landing strategy to deal effectively with high impact loading during landing. Future research is warranted in investigating impact attenuation in landing of participants with significantly different eccentric strength.

KEY WORDS. Eccentric strength, dynamometer, drop landing, training

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Chapter 1

Introduction

Background of the Study

The concept of enhanced athletic performance as a result of greater muscle strength is not a new phenomenon. In an effort to improve the ability to have safer and more controlled landings, generate power while jumping, cutting and sprinting and reduce injuries higher levels of strength are beneficial in sports (33, 55, 78).

Subjects with different training backgrounds have been found to demonstrate different biomechanical characteristics when landing and jumping (11, 12, 34, 51, 52, 55, 75). Highly trained athletes show improved measures of performance and movement biomechanics in comparison to recreational performers (55). In a comparison of drop jump performance in highly trained triple jump athletes and physically active control subjects; triple jumpers jumped higher, had shorter braking and total contact times, and had greater peak vertical ground reaction forces (75). The two groups also differed in their response to increasing drop height, leading to the conclusion that the neuromuscular system of jumpers was better able to withstand the ground reaction forces and high stretching speeds.

During jumping and landing, all lower extremity joints facilitate energy generation and absorption (36). Landing is a necessary consequence of jumping. Each landing applies impact loading to the body, which must be absorbed. The musculoskeletal components of the lower extremities are the primary active absorption mechanism of the body (52, 53, 59, 84). If the loads become too great for the body to accommodate, there is an increase in the potential for injury (19, 59). Landing requires large eccentric knee, hip and ankle extensor muscle forces during the control of joint flexion to decelerate the body. Biomechanical landing studies are beneficial because they simulate the muscular stresses experienced during athletic competition (6, 7, 14, 15, 19, 20, 26, 54, 84).

The training experience of an athlete can impact landing characteristics (5, 11, 20, 48, 51, 52, 65, 75). Highly trained athletes demonstrate improved performance compared to control subjects in the vertical jump as well as show increased knee flexion-extension range of motion (ROM) during landing from a vertical jump (52). Another positive result, likely linked to training related improvements in performance, is a reduction in risks of injury (55). Despite the magnitude of research regarding landing and jumping performance, research is limited regarding the effects of lower extremity strength (especially eccentric) and past experience on landing from different heights.

A method to measure peak torque for muscle contracting at velocities which closely match those achieved during jumping or landing is isokinetic testing. The velocity of movement is controlled and maintained constant by an isokinetic dynamometer. One study analyzed eccentric hip-abductor strength and its relationship to landing (33). Subjects with greater eccentric hip abductor strength had lower peak knee-valgus angles during landing. Increased hip-muscle activity was hypothesized to permit the quadriceps to be more effective at attenuating the forces associated with landing (33).

A positive relationship has been identified between vertical jump performance and strength measured with an isokinetic dynamometer (13, 32, 77, 79). There has been a significant difference in measured variables between elite and amateur performers, including elite players ability to jump higher than amateur performers (12).

Another area of limited research is the effect of different experience or training levels on the biomechanical characteristics of the lower extremities during landing from different heights. It has been suggested that trained athletes have differing capabilities to attenuate the impact forces of landing (11). Non-elite athletes used the hip joint muscle group more, while elite athletes used the ankle and knee joint muscle groups more (11). Individuals who train for power have shown decreased stiffness when landing (31). It has also been reported that a correlation exists between leg strength and vertical ground reaction forces (GRF) in experienced parachutists when compared with non-experienced parachutists (29). It has been suggested that with different conditioning backgrounds and maximum power generation capabilities, differences would exist in impact attenuation during landing (11, 51, 52).

We aim to address the influence of muscle strength on the GRF and kinematics of landing from different heights and the maximal height for a safe and controlled landing.

Problem Statement

Therefore the purpose of this study was to investigate the relationship between impact force attenuation in landing and eccentric and concentric torque generation of quadriceps muscles in TRAINED and REC subjects. Different heights are needed to determine whether TRAINED and REC subjects attenuate differently under different demands. The results from this study may provide information on how eccentric isokinetic strength is related to impact attenuation during landing in jumping activities, the effect of physical strength and experience on landing biomechanics, and gain a better understanding of the relationship of eccentric leg strength and dynamic eccentric performances.

Hypotheses

The following hypotheses were tested

H1: During landing TRAINED subjects use more knee flexion than REC subjects.

H2: During landing TRAINED subjects have smaller GRF peaks than REC subjects.

H3: There is a correlation between peak GRF variables & eccentric knee extensor strength

Delimitations

The study was conducted within the following delimitations:

1. Fourteen, seven TRAINED and seven REC male participants who were healthy were selected from the student population at The University of Tennessee. They had no lower extremity impairments at the time of testing.
2. Each subject performed three isokinetic test conditions, which included concentric knee flexion and extension at two predetermined speeds (60 and 180° $\cdot$ sec^{-1}) and eccentric knee flexion and extension at 60° $\cdot$ sec^{-1}; vertical jump testing, 3 test conditions of drop landing from an over-hanging horizontal bar set at predetermined heights (40, 60 cm and 100% of the subjects maximal jump height that were measured from the mid-heel to the force platform. Biomechanical signals were collected and analyzed for duration from the

ground contact to the maximum knee flexion in all drop landing testing conditions.

3. Data were collected at 1200 Hz for two force platforms and at 240 Hz for a seven-camera motion analysis system for each trial during the biomechanical testing and at two angular velocities (60 and 180° · sec^{-1}) for an isokinetic dynamometer.

Limitations

The study was limited by the following factors:

1. Subjects were limited to the student and athlete population at The University of Tennessee.
2. Possible errors from placement and digitizing for the reflective markers are acknowledged. These errors can be minimized by understanding accurate anatomical information and repeated practice of marker placement.
3. Inherent errors from the force platforms, high-speed video systems and isokinetic dynamometer which are always present but considered acceptable by the biomechanics community and within the specifications of the manufacturers. Proper calibration procedures were strictly followed according to the recommendations of the manufacturers to minimize measurement errors.
4. The accuracy of the spatial synchronization between the 3D kinematic system and force platforms is limited by the accuracy of the placement of the calibration frame (L-frame) of the Vicon motion capture system in relationship to the corner of one of the force platforms. Care was taken in the placement

which was done according to the instruction of the Vicon manual to minimize this potential error.

5. Potential errors may also be due to the difference in sampling frequency of the force platform (1200 Hz) and the high-speed video system (240 Hz), and the synchronization of the systems. Synchronization accuracy between the force and video systems was limited by the sampling rate of the slower system. However, the temporal synchronization is handled internally by the Vicon hardware and software the error was assumed to be minimal.
6. The accuracy of jump height measurements is 1.27 cm (0.5 inch), limited by the inter-spike distance of 1.27 cm on the Vertex system.

Assumptions

The following assumptions were made:

1. The biomechanical equipment and measurements used were accurate and sufficient for analyzing effects of drop landings with differing drop heights.
2. The biomechanical instruments and programs were valid and reliable.
3. All subjects were free from significant injuries in the lower extremities.
4. All subjects were able to become familiar with the isokinetic and biomechanical testing protocol with the pre-testing practice.
5. All subjects completed the experimental tasks to the best of their ability.

Chapter 2

Literature Review

The following section provides an extensive review of the literature as it pertains to the current study. The following topics are discussed in the chapter: a) power generation; b) isokinetic strength testing; c) effect of participation and training level differences; d) landing.

Power Generation

Muscle strength, the ability to produce muscle force and torque, (69) is a key component in determining athletic performance (12, 16). Critical sport skills or abilities such as speed, acceleration, rapid direction change, running, jumping, landing and cutting, may improve by increasing the available force of muscular contraction in certain muscles or groups of muscles. Success in sporting events involving jumping, sprinting, and kicking requires high velocity movements combined with high force generation, necessitating the generation of high power by the musculature involved (12, 21, 69, 71, 82).

An increase in either strength, speed of muscle contraction, or both can lead to increased power production. Power is equal to the force applied multiplied by the speed at which the force is applied (71). Higher levels of strength, speed and power would be beneficial in sports and could help reduce injuries, and allow for more powerful jumps, cuts, sprints, change of direction (55, 78) and allow for safer, more controlled landings (33).

Resistance weight training has been shown to increase muscular strength. “Power” lifting exercises such as bench press, deadlift and squat are commonly used for increasing maximum power. These lifts focus on the generation of force throughout the full range of motion, due to their low velocity. Olympic lift training focuses on the ability to produce maximal forces in a short time period and the maintenance of the force as the velocity of muscular contraction increases (39). Olympic lifts such as the snatch and the clean-and jerk develop power that contributes more to performance enhancement. This type of training is referred to as specificity of training, as the velocity of these lifts is more specific to movements that occur in sport (28, 39).

Explosive type actions such as, jumping and landing, and landing immediately followed by jumping are important factors for successful athletic performance (71). The vertical jump is a skill required in many sports (19).

Physical conditioning plays an important role in improving power generation capacity (17). McBride et al (17) compared sedentary males and females to athletes specializing in strength and power events for peak instantaneous power output during vertical jumps. The results showed no significant differences in peak power in vertical jumps without external loads compared to jumps with external loads of 5 kg and 10 kg for the athletes. However for sedentary individuals the peak power was significantly higher when jumping with no external loads than when with loads. Athletes with higher levels of physical conditioning were able to maintain adequate levels of performance, while performance of sedentary individuals suffers when greater than normal external demands are placed on the body.

The vertical jump is a multi-joint action that requires substantial and concentrated muscular effort from the ankle, knee, and hip joints (43). Power development during the vertical jump depends on the quality, efficiency and coordination of force production of all the joints of the lower extremity; making vertical jump testing a reliable method for evaluating explosive leg power. Because it is a good measure of power and overall leg strength and conditioning, the vertical jump is often used as a measure to predict an athlete's physical ability (9, 71). It is also easy to administer and closely resembles sport specific activity. Several studies have shown a positive correlation between vertical jump and leg strength (8, 56, 71).

In a simulation study using a forward dynamics approach, Bobbert and his colleagues(8) examined the effects of manipulating muscular control parameters and strength variables on vertical jump performance, using a model of the human musculoskeletal system. The results of the simulations indicated that jump height is improved after strength training when combined with learned coordination for the athlete and their stronger muscles. Increased strength alone, without coordination of movement patterns, is not enough to improve vertical jumping performance.

Thomas et al (71) examined the relationship between maximum leg extension power and other tests of muscular power (double leg press power, leg extensor power rig, habitual gait and maximal gait velocity, Wingate anaerobic power test, vertical jump test, 40-yard dash, body composition and habitual physical activity). Nineteen sedentary women participated in this study. It was determined that the maximum power generation of the double leg press occurred at 56-78% of the 1 -RM. Results showed a strong relationship between the double leg press power test, maximum strength (1-RM) and vertical jump height.

Athletes trained in strength demonstrate improved performance in the vertical jump (12, 47, 55, 69). The combination of plyometric exercises along with lower body strength training has been documented to augment jumping performance and power output to a greater degree than plyometric training or weight training alone (22, 56). Myer et al (56) tested the effects of neuromuscular training, plyometrics, core strengthening and balance, resistance training, and speed training on improving performance and lower-extremity biomechanical measures related to anterior cruciate ligament injury risk in female athletes. Forty one female basketball, soccer and volleyball players along with twelve matched controls underwent 6 weeks of training. After the training program athletes improved vertical jumping ability, single-leg hopping distance, sprint time, and one repetition maximums of squat and bench press. Improved landing biomechanics and increased knee flexion-extension ROM were observed during the landing phase of a step-off drop jump. The time on the force plate pre and post training was not different. Prior to training subjects had large medial-lateral knee torques on landing. Valgus and varus knee torques were reduced after training. The control group showed no significant increase in any of the above measured variables following the 6 weeks training. Results indicate that a comprehensive neuromuscular training program designed for injury prevention can improve strength, performance and movement biomechanics.

Athletes who participate in training programs focused on stability exercises, resistance training and deep knee flexion landings are likely to reduce injury and improve athletic performance through learning proper knee alignment when performing jumps and landings, landing with a more bent-knee position, learning to decelerate before a cutting maneuver (25), as well as beneficial adaptations that occur in bones, ligaments and tendons (23, 38).

In another training study, Myer (55) investigated the changes in lower extremity biomechanics following two training programs. Eighteen female athletes were divided into two groups. The main difference between this and the above study is the two different training protocols. In this study, one group preformed plyometric training, while the other group focused on dynamic stabilization and balance training. Two movement tests that may be related to ACL injury were chosen to examine the effects of the balance and plyometric training. 3D motion analysis of drop jump (31 cm) and a single-legged medial drop landing task (13.5 cm) were conducted before and after the 7 week training protocols. For the single-legged medial drop landing subjects stood on a raised block balanced on one leg then dropped off the block medially onto the force platform landing and balancing on that same leg. Both plyometric and balance training resulted in reduced initial contact, maximum hip adduction angle, and maximum ankle eversion angle during the drop jump. There was also a decrease in initial contact and maximum knee abduction angle for both groups in medial drop landing. Initial knee contact angle and maximum knee flexion increased with plyometric training during the drop jump. During the medial drop landing those who were balance trained showed increased maximum knee flexion.

Clearly both plyometric and dynamic stability training were shown to improve landing biomechanics which should lead to improved performance and result in a reduction of injuries. Both training strategies showed the ability to reinforce landing with reduced valgus motion, and with increased knee flexion.

Although athletic performance is not determined solely by measurable variables, such as one repetition maximum strength, jump height and sprinting time, there is a noticeable difference in measured variables between elite and amateur performers. Cometti (12) compared elite, sub elite and amateur soccer players for isokinetic strength and other measures of anaerobic power. Ninety five soccer players (29 elite, 34 sub elite and 32 amateur athletes) performed concentric contractions of the knee extensor and flexor muscles at angular velocities of 60, 120, 180, 240 and $300° \cdot sec^{-1}$, and eccentric actions at 60 and $120° \cdot sec^{-1}$ to assess the difference between the athletes and amateurs. Vertical jump, sprint performance and kicking performance (maximum ball speed) were also compared. Professional players had significantly greater concentric knee flexor peak torque than amateurs at all angular velocities except at $300° \cdot sec^{-1}$. While the three groups of players were comparable in concentric strength, the amateurs had greater eccentric knee extensor peak torque than the professional players. The elite players ran faster over 10 m than the amateur players. There were no significant differences between elite and amateur groups in vertical jump height, 30 m sprint time and in maximal ball speed in shooting (12). The quadriceps play a key role in jumping and ball kicking in soccer while the hamstrings are important for stabilization of the knee during turns or tackles and they eccentrically contract to decelerate when running (24).

Increasing hamstring strength may provide greater stability to the knee joint (12). The elite players in this study only had greater performance values than amateurs in two tests; (knee flexor strength and 10 m sprint time) as a result authors failed to discover a relationship between isokinetic strength and the measured power performances.

Lower limb strength and two Australian football skills were assessed in nineteen sub-elite Australian football players (67). Peak torque of knee flexion and extension at angular velocities of 60, 240, and 360° · sec^{-1} were assessed in a reciprocal concentric manner using an isokinetic dynamometer (Biodex). Isokinetic strength measurements were compared with running vertical jump and kicking performance (distance and accuracy). As test velocity increased absolute and relative knee extensor mean peak torque decreased. Several results indicated significant correlations between isokinetic strength measures and vertical jump height (knee extensor, 240° · sec^{-1}, take-off limb, absolute (r= 0.69), knee extensor, 360° · sec^{-1}, take-off limb, absolute (r= 0.59), knee flexor, 60° · sec^{-1}, take-off limb, absolute (r= 0.55), knee extensor, 240° · sec^{-1}, take-off limb, relative (r= 0.58)) Overall the correlations between running vertical jump and isokinetic strength were low to moderate (0.55-0.69).There was no significant difference found between kicking performance and isokinetic strength data (67). The isokinetic strength measures of this study were compared with previous data on other elite Australian Football players. The mean age, of 21.6 years of the elite Australian football players in the current study was comparable to the mean age of 22 in the previous study, while their weight and height was slightly less than the previous study (35). The mean knee extensor peak torque at 60° · sec^{-1} of the present study was 176.2 Nm and less than that of the previous study which was 203.3 Nm. The mean 60° · sec^{-1} knee flexor peak torque reported by this study of 119.5 Nm was less than the 142.7 Nm found in the past study (35).

Individuals found to have enhanced knee extensor strength may demonstrate superior performance in actions involving knee extension such as running vertical jump. Running vertical jump performance correlated significantly with isokinetic knee strength measures at all angular velocities. Trained players produced greater absolute peak torque values than sub-elite, less trained athletes. Training induced strength differences, greater body mass and genetic differences are possible reasons for the observed difference (67).

In an effort to look at characteristics that predict a person's capacity to exert muscular power, researchers compared vertical jumping and several power tests and isokinetic knee extensions at 120, 180 and 240° · sec^{-1} (45). Four groups of subjects were tested in four different conditions. Group I performed countermovement vertical jumps (CMJ) on the force platform and isokinetic knee extensions. Group II did CMJ trials, 20 m sprints, hand-reach jumps and 1–RM leg-press testing. Group III did squat jumps and CMJ trials. Lastly Group IV carried out only the CMJ trials and were retested two more times on later dates. The results showed significant correlation between the isokinetic knee extension power using an isokinetic dynamometer (Biodex) and the counter-movement jump power which was calculated from all jumping trials resulting from the force platform measurements. Vertical jumping power was normalized to body weight to allow comparisons between individuals of different sizes. Hand-reach height was moderately correlated with vertical jumping power. The correlation of jumping power and isokinetic knee extension power was moderate and largely dependant on the angular speed. The strength of the correlations was found to be highest at the intermediate angular velocity: r = 0.702 at 120° · sec^{-1}, r = 0.737 at 180° · sec^{-1} and r = 0.599 at 240° · sec^{-1}. It was concluded that the counter-movement jump is a highly reliable and valid assessment of lower extremity muscular power, however using this method alone may be too general. Although the reliability of using isokinetic power testing is generally undisputed; using it alone may be too specific to predict overall power capability. Therefore the use of both isokinetic power testing, combined with vertical jump performance has been encouraged for assessment of overall lower extremity power output (45).

Researchers have discovered a significant correlation between isokinetic power and vertical jump performance (41). In this study, authors analyzed isokinetic peak torques values generated by 40 college-age men in comparison with various anaerobic power tests. Knee peak torque values were obtained for the dominant knee during knee flexion and extension at 60 and 240° · sec^{-1} on an isokinetic dynamometer (Cybex II). A criterion measure of total isokinetic power (TIP) was established by summing all of the isokinetic power assessments together. Height, weight, maximal vertical jump, the Margaria-Kalaman power test and cranking power, a modified Wingate power test, were used as the other test measures which the isokinetic power assessments were compared against. A close relationship was found to exist between isokinetic power and the Margaria-Kalaman test, vertical jump, the modified Wingate test. The Margaria-Kalaman test was followed by the vertical jump as the two tests with the highest correlation with TIP (r= 0.84 and r= 0.77 respectively)

The relationship between the mechanical behavior of the leg extensor muscles during isokinetic contractions and ballistic performances of 20 male volleyball athletes was investigated (9). The ballistic activities consisted of squatting jump (SJ), counter-movement jump (CMJ), and drop jumping (BDJ) from heights of 20, 40, 60, 80 and 100 cm which resulted in different stretch loads on the active leg extensor musculature. Peak torque and power output (Cybex II) were measured during knee extension throughout the full 90 degree range of motion at 30, 60, 120, 180, 240 and 280° $\cdot$ sec^{-1} on the dominant leg. The results showed vertical jump performances (SJ, CMJ, and BDJ) to correlate with isokinetic contraction. The isokinetic peak torque at 240º $\cdot$ sec^{-1} produced the strongest correlation with CMJ (r= 0.74). Results reported that the highest power generated during jumping (19.2W/kg), was much greater than the highest power generated during isokinetic testing (6.4W/kg) which is in agreement with the findings by Iossifidou (32). Despite the fact that isokinetic contraction is a functionally unnatural muscular activity, a close relationship was found between it and the muscle activation found during ballistic jumping performances. Both jumping performance and isokinetic dynamometer measures were concluded to be useful for determining explosive power, despite their inherent differences. In jumping performance several joints are used, while subjects are strictly forced to maintain a stabilized joint position during isokinetic dynamometer testing (9).

Successful athletic performance is linked to the athlete’s ability to generate power from their lower body to perform tasks and skills specific to their sport. Training to improve power generation has focused on increasing the velocity of the movement and maximum force during exercises. Improvements in vertical jump height can be a result of improved power generation (8, 43, 56, 71, 74, 81).

Vertical jump testing, which provides information about the mechanical work output of the entire kinetic chain, is a measure of performance and an indirect measure of lower extremity muscle power. Another method, which provides information regarding the strength of specific muscles or muscle groups at a specific pre-set speed, is isokinetic dynamometry (37). However, no acceleration occurs in isokinetic strength measured on an isokinetic dynamometer like it does in ballistic movement such as jumping.

Isokinetic Strength Testing

Isokinetic dynamometry provides information about the muscular torque of a muscle group at joint angles and velocities of movement, the power and work output, the characteristics of the force velocity curve, and the relationship between agonist and antagonist muscle groups.

Open kinetic chain (OKC) isokinetic evaluation allows the tester to isolate individual muscle group for evaluation (37). A standard OKC isokinetic test for concentric knee extension/flexion measures muscle torque, power and work at speeds from $0° \cdot \text{sec}^{-1}$ up to $400° \cdot \text{sec}^{-1}$. The slow repetitions are mainly for strength measurements and the higher speeds for strength and power analysis. Peak concentric knee torques are normally achieved at approximately 72º to 55º toward normal knee extension and at 20º to 45º of flexion for the hamstring muscles (61). Quadriceps-to-hamstrings torque ratios should be about 60-65% at an angular velocity of $90° \cdot \text{sec}^{-1}$

(61). At slow speeds (60º · sec^{-1} to 90° · sec^{-1}) the male athlete quadriceps peak torque development should be approximately 90 to 100% of body weight (61). As angular velocity increases the optimal position for maximum torque tends to navigate closer to 60° in both flexion and extension (61). Regarding the torque-velocity relationship during isokinetic testing, it has been demonstrated that with increasing angular velocity subjects will produce a lower level of muscular torque (3, 61, 72, 80).

Isokinetic testing provides a method to measure peak torque for a muscle contracting at velocities which are moderately close to those achieved during athletic movements, such as jumping or landing from a jump (2).The velocity of movement is controlled and maintained constant by the dynamometer (70). Isokinetic dynamometry testing is often selected over free weights based on its ability to provide information on both knee extensor and flexor torque in concentric and eccentric contractions at different angular velocities. It has become a preferred method of clinical and research assessment of dynamic muscle function (67).

Isokinetic dynamometry has shown the ability to discriminate between athletes of different performance abilities (79). Investigators must remember that success in athletic performance is often multi-factorial, with different movements requiring different combinations of speed and strength of muscular contraction. As a result a single strength measure may not be capable of explaining all athletic performance variance (10, 12, 13, 79). Several limitations exist resulting from the fact that the movements tested are not specific to an athlete’s performance. A major area of concern in isokinetic strength testing relates to the varying speeds of movement in athletic performance verses the constant velocity testing speeds. Constant velocity movements are seldom found in sports, and even the maximal velocities of the isokinetic dynamometer do not reach the velocities often observed in athletic movements (79). Despite these limitations, correlations have been found between isokinetic dynamometry and non-constant velocity athletic movements, even when using angular velocities much lower than those of the compared movement (79). High velocity isokinetic movements are typically in the range of 300-500° · sec^{-1}. Isokinetic movements are also generally single-joint movements. Most high velocity sports movements are ballistic and start with a concentric contraction from a zero velocity typically ending with very high, maximal velocities. For example, the maximum unloaded peak angular velocity for isolated knee extension is around 500 to 700°/s, while during a punt kick, the knee may reach a peak extension velocity of near 2000°/s (79). A limitation of isokinetic dynamometry testing is the restricted and constant velocities through the range of motion, causing the need for interpreting the results with caution (79). Concentric isokinetic performance measures have been predominately used for correlation studies; however athletic actions involving eccentric stretch-shortening cycles also show high correlation with isokinetic output (79).

Studies have found a positive relationship between vertical jump performance and strength measured with an isokinetic dynamometer (9, 13, 32, 73, 77, 79). In general the correlations between strength measures and athletic performance are existent to a greater degree in sports in which strength is critical (79).

Research compared the relationship between isokinetic thigh muscle strength and maximal vertical jump, long jump and standing five step jump in elite runners (77).

Thirty-nine elite runners were examined for thigh muscle strength on an isokinetic dynamometer (Cybex II). Maximum strengths in the knee extensors and knee flexors of both legs at 30 and 180° · sec^{-1} were collected. A statistically significant correlation was found between the performance of all three jump tests and muscular strength measurements at both angular velocities. The correlation was good for the quadriceps ($r = 0.83 - 0.84$) and fair for the hamstrings ($r = 0.61 - 0.77$). The correlation tended to improve with higher angular velocities, with the best correlation occurring at 180° · sec^{-1}.

The relationship between joint power generation during a squat vertical jump and a concentric knee extension isokinetic test was examined (32). The main contributing muscles to isokinetic concentric knee extension tests are the knee extensors, and for that reason knee extension power during a squat vertical jump was measured. Five active participants performed isokinetic testing using an isokinetic dynamometer (Lido) at four different angular velocities (30, 90, 180 and 300° · sec^{-1}), followed by measurements of vertical jump height over a force platform. Peak power for each of the four different angular velocities and the vertical jump were calculated. The results showed the peak power generated during the squat vertical jump to be significantly greater than that in the isokinetic tests. The isokinetic tests, however, only measure one of the muscle groups involved in the vertical jump. The peak power generation was significantly different between the four angular velocities. The correlations between the squat vertical jump and angular velocities increased as the angular velocities increased from slow to fast. The peak power calculated at the highest angular velocity produced the strongest relationship towards the peak power generated in the squat vertical jump. The study concluded that slow velocity should not be used in isokinetic testing as a predictor of squat vertical jump performance (32).

A significant relationship between vertical jump height and isokinetic knee and hip extension torques was documented in a different study (73). Twenty nine males were compared for vertical jump performance and isokinetic torque production of knee extensors, hip extensors, and ankle plantar flexors. Peak jumping height and the total work were used as measures of vertical jump performance for squat and counter movement jumps. Subjects performed five maximum efforts for hip extension, knee extension and ankle plantarflexion at 60, 120, 180° · sec^{-1} on an isokinetic dynamometer (Cybex Norm). The results showed a strong positive relationship between peak jumping height and total work performed by the hip and knee extension moments, but low correlation between jumping performance and isokinetic moment of the ankle plantarflexors.

The relationship between muscular force production, jump technique, joint mobility and anthropometric characteristics such as age, body composition, weight and height was investigated (13). Twenty-three male recreational athletes performed tests of maximal vertical jump, flexibility, the Margaria-Kalamen anaerobic power, and isokinetic concentric/eccentric quadriceps flexion and extension exercises (Kin-Com III) at the speed of 180° · sec^{-1} to measure average force output and average power. The results showed that as body fat and single leg balance (stork balance test) time increased the vertical jump height decreased. Positive correlations were also found between the right calf girth and eccentric force output of the left quadriceps muscle, and the vertical jump performance. In addition, the knee flexion angle during the countermovement, concentric quadriceps force output, lower extremity flexibility, height and body weight were not significantly correlated with the vertical jump. Left eccentric quadriceps average force did correlate, though not significant, with vertical jump performance (13).

To the knowledge of the author, there is a lack of studies investigating the relationship between eccentric quadriceps force and vertical jump, counter movement jump, drop jump, or impact attenuation in landing. Despite vertical jump being a concentric driven movement, eccentric muscle action is related to the counter movement phase of the jump. Landing following the jumping phase is an eccentric movement. Furthermore, a drop jump is divided into a landing phase followed by a jumping phase with eccentric and concentric contractions of lower extremity extensors involved in the respective phases. The relationship between eccentric strength and impact attenuation in landing warrants further investigations. The lack of published data from eccentric testing is partly a result of the concentric-only dynamometers that predominated until the late 1980s and does not reflect the perceived level of importance of eccentric strength data (30).

In summary, isokinetic dynamometry testing is widely chosen for its ability to provide information on both knee extensor and flexor torque in concentric and eccentric contractions at different angular velocities. When measuring muscular strength using the isokinetic dynamometer the use of slow repetitions is encouraged. Concentric isokinetic performance provides information about the power and work output an individual is capable of and has been shown to correlate with concentric and eccentric athletic actions.

There is a positive relationship between vertical jump performance and muscular strength measured with an isokinetic dynamometer. Isokinetic dynamometry has shown the ability to discriminate between athletes of different performance abilities. The strength of the correlation between strength measures and athletic performance tends to be greater in sports in which strength is of greater importance. Advancements in technology are allowing for more eccentric testing, but to date it is still an area that warrants more investigation.

Effects of Participation and Training Level Differences

There has been a minor focus in the literature placed upon the effects of participation level or past experience (e.g. trained or recreational athletes) on impact attenuation capacity in jumping and landing (11). The GRF differences during landing in relation to leg strength and power between novice and experienced parachutists were investigated (29). Fourteen male soldiers were placed into two groups based on past parachute training experience, parachute training instructors who were highly experienced in parachute jumping and novice jumpers who had no prior parachute jumping experience. For each subject, power output was measured by one repetition maximum squat and maximal jump power was calculated as the product of the mean vertical force and velocity of 15 counter movement jumps. Both groups of parachutists landed from jumps at four different heights (95 cm, 120 cm, 145 cm and 170 cm) onto a force plate that measured ground reaction forces and time to peak GRF at landing. They found no differences in either the squat strength or the maximum jump power between experienced and novice jumpers. However, there was a significantly greater GRF observed in experienced verses novice jumpers. A positive correlation was found between maximal jump power and GRF in experienced jumpers, but not novice jumpers. Correlations between maximum jump power and the time to the peak GRF of the experienced jumpers were all negative, while the correlations between these variables of the novice jumpers were all positive (29). These results suggest that experienced parachutists may use a different landing strategy than novice jumpers, as reflected by differences in GRF generated during impact and a more efficient utilization of muscle power during the impact phase in landing and that the experienced jumpers were able to tolerate greater GRF than the novices.

Studies have found differences in strength and anaerobic power characteristics between elite and non elite performers. Differences were found between high and low level soccer players from measures of concentric isokinetic peak torque of the quadriceps and hamstring muscles. High-level soccer players were concluded to have greater strength as a result of increased training intensity (60). In one study, (72) it was found that elite sprinters in comparison with sedentary subjects had shallower torque-velocity slopes, reflecting their ability to generate a greater proportion of maximal strength during higher velocities. In contrast Barnes, (4) discovered similar torque-velocity slopes between elite sprinters and control subjects, questioning the relationship of maximal strength to performance.

To investigate the relationship between impact velocity and landing experience, McNitt-Gray et al compared recreational athletes and gymnasts for differences in landing strategies (51). Ground reaction forces and joint flexion were collected for landing from 3 drop heights; 32, 72 and 128 cm. Increases in drop height led to several adjustments in landing technique in both groups. As drop height increased, the mean landing phase durations increased in the recreational athletes increased, but decreased slightly for the gymnasts. Gymnasts reached peak force values earlier in landing phase, and were less sensitive to increases in landing height than recreational athletes. There were minor differences in the angular positions of the ankle, knee, and hip joints upon contact between all subjects. Gymnasts had slightly greater extension of the knees (medium, 160.6º; high, 160.2º) and ankles (medium, 132.7º; high 133.3º) when landing from medium and high heights than the recreational athletes (knee: medium, 156.4º; high, 154.8º; ankles: medium, 129.6º; high 128.8º). As landing height increased both gymnast and recreational athletes reduced their knee joint angles. Recreational athletes were found to be more sensitive to increased landing height than gymnasts as seen in the increased range of hip joint excursions. Recreational athletes had a range of 31.3º from the low to 105.5º from the high landing, while gymnasts had a range of hip joint excursion from 58.8º from the low to 91.1º from the high height. There was a significant increase in joint flexion, though not the ankle joint, angular velocity and magnitude impact force in both groups as landing heights increased from low to high. The gymnasts experienced greater magnitudes of mean peak impact forces (11.0 BW) than the recreational athletes (9.1 BW). The authors indicated that recreational athletes and gymnasts do use slightly different landing strategies. The gymnasts seem to have better ability to attenuate impact forces, possibly due to their familiarity with landing or their training background.

Gymnasts may use a uniform landing strategy of similar duration under varied heights based on the training they have to always perform a competition style landing (51).

In a follow up article using the same data set, authors compared the changes in lower extremity kinetics of the same three drop landings (52). They identified kinematic differences in landings from similar heights between recreational and gymnasts. Elite gymnasts dissipated more energy with ankle and hip extensors at the higher height in comparison to recreational counterparts. A higher impact velocity corresponded to an increase in the magnitude of all extensor joint moments suggesting that the active musculature plays a large role in controlling the motion of the lower extremities as the velocity of impact increases. The greater peak extensor moments suggest the knee extensor muscles experience relatively larger demands than the ankle and hip when landing from higher heights. The increased landing height also produced an increase in ankle, knee, and hip peak extensor moments and work, increases in peak ankle, knee, and hip angular velocities, and peak vertical reaction forces. Mean joint moment power curves demonstrated the majority of the work done by the extensor muscles of the ankle, knee, and hip occurred during the first 50% of the landing phase. Body position in preparation for landing was similar regardless of landing height. The extended position of the joints upon landing provides the subject the potential to use maximal range of joint motion during the landing phase. As a result of increased landing height subjects' demonstrated increased joint flexion (especially at the knee and hip), peak joint angular velocities, and peak vertical reaction forces. The sequencing of segmental and joint kinematic events remained consistent over impact velocities. The joints or segments most proximal to the application of the reaction force were brought to rest prior to joints more distal. It was concluded that an increase in drop height caused a rise in peak extensor moments and work done on the extensor muscles of the ankle, knee and hip during drop landings from three heights (52).

In summary, elite performers tend to have greater strength. As landing height increases participants will adopt a landing strategy that leads to increased joint flexion, angular velocity and magnitude of impact force. Individuals will tend to select a landing strategy that best suits their trained performance needs. The neuromuscular system of trained athletes appears to be better able to resist ground reaction forces and allows for quicker response.

Landing

The vertical jump is a skill required in many sports (19, 75). The vertical jump is a multi-joint movement that requires substantial muscular effort from the ankle, knee, and hip joints (43). As an athlete falls through the air to land from a vertical jump, they generate kinetic energy. The goal of landing is to successfully dissipate kinetic energy through work performed by muscles of the lower extremity. The impact forces produced during landing can reach a magnitude of 2 to 12 times body weight (19, 49-51, 54, 64) and can possibly result in lower extremity injury (33). Landing requires large eccentric forces from the quadriceps, hip extensors and ankle plantarflexors to control joint flexions and to decelerate the body (52). Biomechanical studies on landing are beneficial because they examine loading experienced at lower extremity joints during athletic competition (14). Changing the biomechanical strategy for landing is possible through a greater understanding of the factors that influence the body’s ability to absorb impact forces. This knowledge may provide theoretical and practical foundations for the reduction of lower extremity injuries (27).

The ability to control and adequately absorb high-impact forces during dynamic, functional movements is of particular importance to the prevention of injury. Ground impact forces and loading rate were examined during a single-leg landing study (27). Forty-eight volunteers were placed into three groups (supinators, neutral, pronators) and performed single leg drop landings onto a force platform. All three groups of subjects produced similar peak vertical forces (3.57, 3.65 and 3.44 x BW respectively) and had matching loading rate values (0.06, 0.06 and 0.05 BW/ms respectively) during landing from a height of 30 cm. Knee flexion angle (r= -0.281) and loading rate (r= -0.486) correlated significantly with peak vertical ground reaction force (27). The results showed that knee flexion is a major factor in force absorption during landings and are in agreement with previous findings (15, 19, 84).

The use of leg muscles as shock absorbers during landing was investigated theoretically and through experiment (53). Unlike jumping, where the maximum attainable height during the flight phase is easily calculated, it is difficult to determine the maximum (and safe) height for a step-off landing. The landing performance of sedentary subjects and elite athletes were compared when landing from different heights and when different strategies of force dissipation were used. Group one consisted of four healthy males who performed drop landings from three heights (0.4, 0.71, and 1.1 m). Landing from a height of 0.75 m, Group 2 was comprised of 36 elite skiers. Subjects were instructed to land flat footed and to stop their downward movement as quickly as possible. The derived muscle force-velocity relationship for eccentric contraction speeds indicates an increase in the negative power with increased drop height. Peak power was concluded to be an indirect predictor of the ability to stop downward movement as quickly as possible when landing from a jump. The sustainable peak force a subject can withstand determines the minimum duration of the landing phase while the maximum duration is determined by the available downward displacement following touchdown. It was inferred that for a given body size the only method to improve the capacity of controlling a drop landing is to increase muscular strength.

The biomechanics of landing has been studied extensively (6, 7, 15, 19, 20, 26, 27, 50, 54-56, 84). In general the past landing studies have focused on the prediction of impact forces, comparing landing techniques, effects of landing velocity, and changes caused by height, distance, and technique. Landing height has been shown to have a close relationship with the magnitude of peak GRF (19, 27, 49-52, 54, 62, 84). Six recreational athletes landing from 0.32 meters were found to have mean ground reaction forces (GRF) of 3.93 times body weight (51). 16 subjects landing from a similar height mean GRF were observed to be 4.6 times body weight (49). When landing from a higher height (0.40m), mean peak GRF of three subjects was 3.85 times body weight (19), while mean GRF of five subjects landing from 0.5 meters was in the range of 1.67 to 6.18 times body weight (54). Another study examined vertical GRF generated from barefoot landings in gymnasts following a dismount from a horizontal bar. Gymnasts first landed onto a mat covering the force platform from 2.55 m above the floor and then directly onto the force platform from a 0.45 m drop height (62). The vertical ground reaction forces ranged from 8.2 to 11.6 BW, in comparison to vertical ground reaction forces ranging from 5.0 to 7.0 BW when doing a normal landing onto the force plate.

Landing from greater landing heights results in greater vertical GRF (VGRF) was confirmed in another study (54). Peak VGRF (F1, the first peak which results from initial ground contact with the toes in toe-heel landing and F2, which represents the second peak resulting from the heel contact) and range of motion for the hip, knee, and ankle joints were examined in several landing conditions. Five subjects performed drop landings using both a toe-heel and flat footed landing strategy from a low height (0.5 m), and toe landings from the higher position (1 m). A toe-heel landing style decreased peak forces significantly for all subjects when compared to landing flat footed. When landing from an increased landing height, toe-heel landing strategy utilized greater ranges of motion for the hip, knee, and ankle joints than when landing from lower heights. The results highlight ability of joint motion and muscle action in reducing peak GRF during landing.

In an extensive study on landing the relationship between height, distance and technique on impact forces was evaluated (19). Three male participants completed a total of 81 trials, performing three landing trials in each condition. Landing test conditions included a combination of landing from three distances (40, 70 and 100 cm), from three landing heights (40, 60 and 100 cm) using three different landing techniques (stiff knee, slightly-flexed knee and fully-flexed knee). High-speed video and a force platform were used to collect data; peak vertical ground reaction forces (F1 and F2), times to F1 and F2 and sagittal kinematics were examined. The increases in peak VGRF were a product of increased landing height and landing stiffness. F1 and F2 were greater with stiff landing than with fully flexed landing and the time to F1 and F2 decreased from fully flexed to stiff landing. A toe-heel landing strategy produced lower F2 values than subject three who landed flat-footed. It was recommended that participants in activities with lots of landings should focus on using a toe-heel contact pattern with greater knee flexion.

In an effort to improve upon the usually small sample sizes for landing studies and provide more normative data of vertical ground reaction forces, ground reaction force data on 234 secondary school students (13-19 years) landing from a jump were collected (50). Subjects were categorized by activity level, type of sport played and gender. Subjects landed onto a force platform from a 0.3 m box. Based on the number of days per week subjects participated in sport (4-7 high activity; 1-3 low activity) subjects were placed into high and low activity groups. They were also grouped according to whether they participated in jumping or non-jumping sports. The mean peak vertical GRF for all students was 4.5 BW. The mean peak vertical GRF was 4.6 BW for males and 4.2 BW for females. The subjects participating in jumping sports had a mean peak vertical GRF of 4.6 BW, while non jumping athletes had a mean peak vertical GRF of 4.4 BW. The mean peak vertical GRF of the high activity group was 4.5 BW and 4.4 BW for the low activity subjects (50). No significant differences were observed across or between the above factors.

Vertical ground reaction forces and loading rates of aerobic dance movements were compared (66). Five trials of two aerobic dance movements, high and low impact knee lifts, were performed by five dancers. It was found the mean peak ground reaction forces were significantly lower in the low impact knee lift (0.98 BW) than in the high impact knee lift (1.98 BW). Mean loading rate was significantly lower on the low impact knee lift (14.38 BW/s) than the high impact knee lift (42.55 BW/s). These results demonstrate that a low impact knee lift creates a significantly lower load than a high impact knee lift (66).

The relationship between different landing heights and techniques and the changes in the contributions of lower extremity joints to energy absorption were investigated (84). Using three different landing strategies (soft, normal and stiff), nine active males performed step-off landings from three different heights (0.32, 0.62 and 1.03m). As height and stiffness increased, there was an increase in peak GRF, peak joint moments, and power. The soft and stiff landing techniques and three landing heights produced significant differences in F1, F2, and knee ROM. For stiff landings the time to the minimum position of center of gravity was less than 200 ms and for soft landings it was close to 300 ms. Knee joint extensors where found to be consistent contributors to energy dissipation. The ankle joint musculature was more involved in stiff while hip contributed more in soft landing. There was a shift of energy absorption from distal to proximal muscle groups with increased muscular demand as landing height increased. Hip extensors become more involved as mechanical demand increased due to the massive potential of energy reduction for the muscle group. Ankle plantarflexors exhibit less capacity for energy absorption, and are more important in the stiff landing at lower heights (84).

Landing technique is a determinant of the resulting magnitude of GRF; a stiffer landing results in a greater GRF value. Both an increase in landing height or landing stiffness will generally result in increased load placed on the body (84). During landing, high impact forces are imposed on the body. Muscle action and multi-joint motion during the early phase of impact has proven important in the relationship of the magnitude peak VGRF. Better attenuation is the result of increasing the flexion range of the joints of the leg, through a decrease in stiffness and an increase in contact time during impact (54).

Through studying the effects of landing techniques on impact force in landings it was demonstrated that a reduction in vertical ground reaction forces is closely related to increased knee flexion (68). This results agree with other findings (54, 84). The range of peak vertical ground reaction forces in toe landings were smaller in magnitude than those of toe-heel landings; 1000 to 2000N and 1000 to 6500N respectively. More knee flexion during the landing phase will likely reduce the chances of injury due to lower ground reaction forces and better shock absorption. More knee flexion at the time of maximum ground reaction force is related to lower peak ground reaction force values(68, 46).

Many studies have attempted to quantify ground reaction forces experienced during the landing phase of jumping movements. Lees (42) observed that landings can be divided into impact absorption (first 150 to 200 ms of stance) and balance phases. Nigg (57) defined forces that reach a peak in less than 50 ms as passive forces. Since these forces are applied at a rate that is faster than the reaction time of the neuromuscular system (50 -75 ms), the muscles are unable to react fast enough to absorb the shock via flexion of the ankle, knee, and hip joints. Ineffective attenuation of passive forces may result in microtrauma to soft tissue and bone. In landing movements, peak impact force, loading rates, high-frequency impulse increased with increased jump height, while time to peak vertical impact force decreases with increasing height (18, 19, 51, 68).

Neuromuscular training, plyometrics, core strengthening and balance, resistance training, and speed training was determined to improve performance and lower-extremity biomechanical measures related to anterior cruciate ligament injury risks in female athletes (56). After 6 weeks of training, female basketball, soccer and volleyball players improved landing biomechanics by increasing knee flexion-extension ROM during the landing phase of a box drop jump. Despite the increase in ROM, the time on the force plate pre and post training did not change. Prior to training subjects had large varus and valgus knee torques on landing. Valgus and varus knee torques were reduced after training. The right knee internal valgus torque decreased 28% and the right knee internal varus torque decreased 38%. While the left knee torque values showed similar trends the results were not significant. The results indicate that a comprehensive neuromuscular training program designed for injury prevention can improve strength, performance and movement biomechanics.

Athletes who participate in training programs focused on stability exercises, resistance training and deep knee flexion landings are likely to reduce injury and improve athletic performance through learning proper knee alignment when performing jumps and landings, landing with a more bent-knee position, learning to decelerate before a cutting maneuver (25), as well as beneficial adaptations that occur in bones, ligaments and tendons (23, 38).

In another training study the changes in lower extremity biomechanics following different training programs were investigated (55). In this study, one group preformed plyometric training, while the other group focused on dynamic stabilization and balance training. Two movement tests that may be related to ACL injury, drop vertical jump (31 cm) and a single-legged medial drop landing task (13.5 cm), were chosen to examine the effects of the balance and plyometric training before and after the 7 week training intervention. For the single-legged medial drop landing, subjects stood on a raised block balanced on one leg then dropped off and landed onto a force platform balancing on that same leg. Both plyometric and balance training resulted in reduced initial contact and maximum hip adduction angle, and maximum ankle eversion angle during the drop jump. There was also a decrease in the initial contact and maximum knee abduction angle for both groups in medial drop landing. In addition, the initial knee contact angle and maximum knee flexion increased with plyometric training during the drop jump. During the medial drop landing those who were balance trained showed increased maximum knee flexion. Clearly both plyometric and dynamic stability training were effective in improving landing biomechanics which may result in a reduction of injuries. Both training strategies showed the ability to reinforce landing with reduced valgus motion, and with increased knee flexion.

During landing and jumping, all lower extremity muscles and joints facilitate energy absorption and generation (36). Although landing takes place in less than half a second, the ‘impact absorption’ lasts from 150-300 ms depending on the type of landing (62). Joint movements and muscle action play a major role in reducing peak forces during landing (54, 62). Impact forces (F1 and F2) and joint moments of force during landing have been intuitively linked to injury potential. Greater forces and torques subject to the body which must be accommodated or attenuated or if excessive, may lead to injury (58). There are several factors which an athlete can manipulate during landing such as landing velocity, geometrical alignment, and muscle tuning which influence impact forces acting on the human body (58). Impact attenuation can happen passively or actively. The passive mechanism is achieved by bone, soft tissues, and footwear. The active mechanism through eccentric muscle contraction is much more significant. Ideally, both shock-absorbing mechanisms work together. When deformation starts in the passive mechanisms, a neurological feedback system senses the increased force and brings the muscles and joint actions as a result of muscle contraction into play before the forces have time to reach destructive levels (54). After contact, the muscle tendon units must generate sufficient force to stabilize the joints, control joint flexion, and reduce total body momentum (59).

Although a direct correlation does not exist, it can be hypothesized that the magnitude and rate of impact force application are two dependant variables that lead to impact related injury (57). Factors such as landing height, speed of movement, body weight, landing strategy, shoe type and landing surface have an influence on the magnitude and rate of loading (51, 52, 65, 66).

Summary

The majority of the research in biomechanics and physiology of muscle performance has focused on the generation of power rather than power dissipation.

However there are many activities and sport and daily living where negative work and deceleration significantly contributes to injury prevention and overall performance and occur as frequently as accelerations. Often for each deceleration, the negative work almost equals the positive work. Activities such as landing from a jump mainly rely on the hamstring muscles to serve as a mechanical brake, developing tension as they are activated during stretching. Choosing a given energy dissipation strategy could have injury and performance implications, and is therefore very important. In athletic competition a longer, soft landing may allow for a more controlled landing, while a quick landing may be beneficial in a landing which needs to be followed by a sudden change in direction or if only a sub-maximal jump is necessary following landing. The investigation of drop landing will provide insight towards the dynamic aspects of muscle braking. Questions we aim to address include: the influences on muscle mechanical characteristics on the kinetics and GRF of landing from different heights and the maximal height for a safe and controlled landing in relation to individual muscle strength. This chapter highlights methods of power measurements and the biomechanics of landing and jumping activities. The emphasis in the literature was placed on evaluating performance based on different levels of strength. However, the research addressing the relationship between strength measures and dynamic eccentric actions and their roles in impact attenuation related biomechanical changes is quite limited. Further investigations of landing and performance differences attributed to subject strength differences are warranted.

Chapter III

Methods

The current study was conducted to investigate the relationship between biomechanical characteristics related to impact force attenuation in landing activities and eccentric and concentric torque generation of the knee extensor muscles by using TRAINED and REC subjects. The results from this study provide information on how eccentric strength is related to impact attenuation during landing activities, the effects of physical strength and past sport experience on landing biomechanics, and a better understanding of the relationship of eccentric leg strength and dynamic eccentric performances.

Subjects

Fourteen healthy male subjects were recruited and volunteered to participate in this study from the student population at the University of Tennessee and were placed into one of two experimental groups: seven healthy and physically active NCAA Division I football athletes, (age: 19.86 ± 0.90 years; height: 1.81 ± 0.03 m; weight: 87.90 ± 4.11 kg) were placed in the TRAINED group and seven healthy males with lower levels of physical activity (age, 23.00 ± 4.16 years; height, 1.73 ± 0.07 m; weight 73.27.0 ± 8.05 kg) were placed in the REC group (Table 1).

Table 1. Mean (± SD) physical characteristics of the subjects.

Group	Age (yrs)	Ht (m) *	Wt (kg) *
REC (n=7)	23±4.16	1.73±0.07	73.27±8.05
TRAINED (n=7)	19.86±0.90	1.81±0.03	87.90±4.11

* Significant difference (p<0.05) between the TRAINED and the REC group.

All subjects were of normal health as determined by a health history questionnaire. The TRAINED athletes followed a structured training program on average 14.7 hours per week, participating mainly in vigorous intensity (7.9 hours per week) weight lifting for power and speed, as well as active warm-up with flexibility and cardiovascular training. The TRAINED group did 6.8 hours a week of moderate activity. The TRAINED group included four defensive backs, two wide receivers and 1 tail back. One source of exercise for the REC subjects' included moderate intensity activities through the enrolment in courses offered in the Physical Education and Activity Program at UTK (folkdance, walking, weight training), but also included recreational sport which totaled about 7.0 hours a week (3.6 hours per week of vigorous and 3.5 hours per week of moderate activity). In most cases three of these hours were through participation in their Physical Education classes. Prior to commencement of the testing session, all participants were briefed on the purpose, procedures, risks, and benefits of the study, signed informed consent (Appendix A) approved by the Institutional Review Board and were free from lower extremity injury for the past 6 months. To assess physical activity levels and past training experiences a Physical Activity Survey, (see Appendix B) was administered. The Survey used some questions from the Behavioral Risk Factor Surveillance System Questionnaire (BRFSS) with additional questions added about participation, frequency, intensity and duration of strength training other specific sporting activities performed during a typical week and injury history

Instrumentation

Biodex System 3: An isokinetic dynamometer (Biodex Medical System, Shirley, New York, USA) was used to measure the peak muscle torque in eccentric and concentric knee flexion and extension exercises at two selected angular velocities (60 and 180º/second).

3D High-speed Video System: A seven-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., UK) was used to obtain the three-dimensional (3D) kinematics during the biomechanical testing session. Sixteen anatomical (1st and 5th metatarsal heads, medial and lateral maleoli, medial and lateral epicondyles, right and left iliac crest, and greater trochanter) and 26 tracking (pelvis, thigh, shank, foot) were placed on both feet, ankles, and legs and thighs and pelvis during testing.

Force Platform: Two force platforms (1200 Hz, American Mechanical Technology Inc., Watertown, MA, USA) were used to measure the ground reaction forces (GRF) and the moments of forces during the biomechanical testing session. The data collection of the 3D kinematic and force platforms was conducted simultaneously via a 16-bit A/D converter in the Vicon system using Vicon Workstation software (Version 4.5.2, Vicon Motion Analysis Inc, UK).

Vertec Stadiometer: (Sports Imports, Hilliard, OH) was used to measure maximum vertical jump height.

Visual3D: Visual3D (C-Motion, Inc.) 3D biomechanical analysis software suite was used to compute 3D kinematic and kinetic variables.

Customized software: A customized computer program (MS VisualBASIC 6.0) was used to determine critical events and compute additional variables from Visual3D outputs. Footwear: All subjects wore a pair of lab shoes (Adidas, USA) during the biomechanical testing session.

Experimental Protocol

Each participant attended two different testing sessions held on separate days with a minimum of three days between the two test sessions. In the first session participants performed an isokinetic strength assessment of the dominant knee flexors and extensors. During the second testing session maximal vertical countermovement jumps were assessed and biomechanical measurements were conducted on drop landing movements.

Isokinetic Assessment: In the first testing session the participant began with a normal warm up of at least 4 minutes of treadmill running/stationary bike at a preferred speed and at least 3 minutes of stretching. The dominant leg was chosen based on which leg the participant would use to perform a single leg jump. The specifications provided in the manufacturer's service manual were used for calibration of the Biodex dynamometer at the beginning of each session. The participant sat upright in the Biodex dynamometer chair and was fastened using the thigh, pelvic, and torso Velcro straps to limit body movement in the chair. The axis of rotation of the dynamometer was aligned with the axis of rotation of the knee, the lateral femoral condyle and the shin pad was secured so its lower edge was positioned 2 cm above the lateral malleolous. The participant was tested for both concentric and eccentric muscular torque production. During concentric testing the participant was instructed to extend and flex the knee through full range of 90° knee motion starting from 90° of flexion. Concentric testing consisted of 2 sets of 5 repetitions at each of two speeds (60 and 180º/sec): 1 practice set and 1 test set. During eccentric testing, participants resisted flexion and extension as the dynamometer moved their leg through the full range of 90º knee motion. At speed a speed of 60º/sec, the participant performed 2 sets of 5 repetitions: 1 practice set and 1 test set for eccentric testing. Verbal encouragement was provided by the investigator and the participant was instructed to fold their arms across their chest to prevent additional body movements. Between testing conditions, participants had at least 90 seconds rest. The order of the speeds and contraction type was randomized. The highest torque values of the flexors and extensors of the dominant leg during concentric and eccentric testing were recorded by the System 3 data collection software and were used for further analyses.

Biomechanical Testing: During the second test session the participant started with the same normal warm up. The standing reach heights with the heels on the ground and raised and vertical jump heights were measured at the beginning of the session. The subject was instructed to stand with both feet flat on the floor and their dominant side facing the Vertec vertical jump testing device. The participant was instructed to perform three countermovement jump trials and used the dominant hand to reach up and swipe the sticks on the Vertec. The participant was instructed to perform several practice trials before the actual testing measurements were taken. The jump heights were recorded. The actual jump heights were computed as the difference between the jump reach heights and the standing reach height with heels down. The highest jump height for each participant was used to determine the actual height of drop landings and drop jumps for one of the conditions in the data collection and for further analysis.

Following the assessment of the jump height, the participant will be outfitted with 16 anatomical and 26 tracking markers. Following a static calibration the anatomical markers were removed and the participant proceeded to perform drop landings. The participant performed five successful trials in each of three conditions, for a total of 15 jumps. The three conditions included drop landing from three heights: 40, 60 cm and 100% of the individuals maximum jump height. The drop landings were performed from an over-head horizontal bar controlled by an electrical hoist from the three heights measured from the mid-heel to the force platform. The participant was instructed to land symmetrically and in balance with one foot on each of the two force platforms and bring the total body center of gravity (COG) velocity to zero and the body position to an upright posture using a normal landing technique. The arms were kept in front of the body during the landing task. Simultaneous recording of kinematics and ground reaction forces were performed during the movements. The participant was given ample time to practice drop landings prior to the actual testing. The order of the landing height testing was randomized.

Data Processing and Analysis

All markers were processed in the Vicon system. The 3D marker trajectories collected on the Vicon system were labeled and reconstructed using the Workstation software and saved in a C3D format. The 3D trajectory and force platform data were then imported and analyzed in Visual3D to compute 3D kinematic variables. The 3D kinematic and GRF data were smoothed with a 4^{th} order low-pass Butterworth filter using a 8 Hz and 50 Hz cutoff frequency, respectively. A customized computer program (MS

VisualBASIC 6.0) was used to determine critical events and compute additional variables from Visual3D outputs. GRF and moment signals were converted to Newtons and Newton-meters respectively using conversion factors. GRF values were normalized by mass (kg) which resulted in a unit of N/kg.

Variables of Interest

The GRF and kinematic variables of interest in this study included the peak GRF (F2) in the landing phase, the time to peak GRF (TF2), contact and peak flexion angle of the knee, ROM of the knee and contact and maximal angular velocity of the knee joint during the landing. The landing phase was defined as the time period from initial contact to the time of maximum knee flexion. Strength related variables of interest included vertical jump and relative maximum peak torque (PT).

Statistical analysis

Descriptive statistics were calculated for all variables. Two-tailed independent t-tests were used to compare vertical jump height and relative PT values between TRAINED and REC subjects. The 2 × 2 mixed-design ANOVA calculated the effect of group (TRAINED, REC) and landing height (40cm, 60cm) on selected vertical GRF variables. Knee kinetic variables were evaluated using a mixed-design 2 x 2 (group x height) repeated measures analysis of variance (ANOVA). An independent samples t-test was used to compare the GRF and knee variables at the 100%MJH. The strength measures were evaluated using a mixed-design 2 x 2 (group x speed) repeated measures ANOVA. An alpha level of $p \leq 0.05$ was selected to indicate statistical significance. Pearson product correlation coefficients were used to determine the relationship between isokinetic strength and peak GRF variables. Statistical analyses were conducted using SPSS version 15.0.1

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Chapter 4

Impact Force Attenuation in Landing and Isokinetic Strength of Knee Muscles in individuals with different training backgrounds

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ABSTRACT

Skeletal muscle is a major active mechanism of impact force attenuation in human movement. During the landing phase impact attenuation is achieved through eccentric contraction of the lower extremity muscles. Few studies have investigated the effects of knee strength on impact attenuation during landing. The purpose of this study was to examine effects of knee eccentric strength on impact force attenuation during landing. Seven NCAA Division I College football players (TRAINED) and seven recreationally active university students (REC) participated in two testing sessions. Isokinetic testing of the knee extensors and flexors was performed concentrically at 60 and $180°\cdot sec^{-1}$, and eccentrically at $60°\cdot sec^{-1}$. 3D kinematic and ground reaction force (GRF) data were collected during drop landings from 40, 60cm and 100% of each individuals maximum jump height. The TRAINED had greater concentric strength, vertical jump, but no significant differences existed in eccentric strength (336 vs 340 N.m/kg) between the groups. The TRAINED had a trend of greater peak GRFs (2.7 & 3.5 vs 2.0 & 2.7 BW for 40 and 60 cm, p=0.051) and significantly less time to the peak (0.048 & 0.043 vs 0.060 & 0.053 s) compared to the REC in landing. The TRAINED used less but non-significant knee flexion range of motion (-60.7 & -54.1 vs -62.7 & -69.6 º) during drop landing than the REC. There were positive significant correlations between the peak eccentric knee extensor torque and time to the first and second peak GRF. Despite training the results did not find any significant differences in eccentric strength of the TRAINED subjects in comparison to their REC counterparts. The TRAINED subjects adopted a stiffer landing strategy to deal with impact loading during landing.

KEY WORDS. Eccentric strength, dynamometer, drop landing, training

INTRODUCTION

Each landing applies impact loading to the body, which must be absorbed. The impact forces produced during landing can reach a magnitude of 2 to 12 times body weight (7, 19, 21). If the loads become too great for the body to accommodate, there is an increase in the potential for injury (7, 25). The muscular system is the primarily active absorption mechanism of the body (20, 25, 39). Landing requires large eccentric forces from the quadriceps, hip extensors and ankle plantar flexors to control joint flexions and to decelerate the body (20). The ability to control and adequately absorb high-impact forces during dynamic, functional movements is of particular importance to the prevention of injury.

Individuals with different strength training and athletic backgrounds have demonstrated different biomechanical characteristics when landing (2-4, 8, 10, 18, 20, 23, 29, 34). When landing, trained athletes have shown improved measures of performance and movement biomechanics such as an increase in initial knee contact angle and maximum knee flexion (8, 20, 22, 34) and lowered vertical ground reaction forces (29, 34) in comparison to non elite performers. During jumping and landing, major muscles across all lower extremity joints facilitate energy generation and absorption (13). It has been suggested that with different conditioning backgrounds and maximal strength capabilities, differences would exist in impact attenuation during landing (3, 19, 20). Despite the wealth of literature regarding landing performance and strength, research is limited regarding the effects of lower extremity strength, especially eccentric strength on landing attenuation characteristics from different heights.

Isokinetic strength testing is often used in research because it can measure muscle torque at velocities that closely match those achieved during sport. Positive relationships have been identified between vertical jump performance and strength measured with an isokinetic dynamometer (11, 30, 33, 36, 37). Trained participants (higher division soccer and basketball players, and jump squat, plyometric and stabilization trained individuals) jump higher (4, 17, 22, 31) and have greater knee flexor peak torque (4, 26, 35, 38) compared to lower level or less trained subjects. In one study, elite, sub-elite and amateur soccer players had comparable concentric knee extensor strength(4). The elite soccer players had significantly lower eccentric knee extensor peak torque than the amateur players during eccentric knee extension (4).

Therefore, the purpose of this study was to investigate the relationship between vertical ground reaction force, knee kinematic variables during drop landing and concentric and eccentric torque generation of quadriceps muscles in TRAINED and REC collegiate participants. The following hypotheses were tested: The following hypotheses were tested. During landing TRAINED subjects would use more knee flexion than REC subjects. During landing TRAINED subjects would have smaller GRF peaks than REC subjects. We also hypothesized that there would be correlation between peak GRF variables & eccentric knee extensor strength for both groups.

METHODS

Approach to the Problem

Although there is evidence that TRAINED subjects jump higher and are stronger than REC subjects there is little research focusing on performance differences in eccentric strength and landing mechanics. Therefore, to determine differences between TRAINED and REC participant's eccentric strength and impact force attenuation in landing, isokinetic strength of knee extensor muscles and biomechanical landing were evaluated. Changes in landing height in the laboratory replicate the mechanical demands placed on the body when landing from a jump at different heights in order to see if TRAINED and REC athletes attenuate differently under differing demands. The use of both TRAINED and REC participants with different leg strength is necessary to observe whether landing performance has any relationship to differences in leg strength. A better understanding of the mechanical demands placed on the lower extremity of the body is gained by examining the changes in landing style relative to landing height and leg strength. This study examined the relationship between isokinetic leg strength and vertical jump ability on landing biomechanics.

Subjects

Fourteen healthy male subjects were recruited from the University of Tennessee student population to participate in this study. Seven NCAA Division I football athletes participated in this study as the TRAINED group (age: 19.86 ± 0.90 years; height: 1.81 ± 0.03 m; weight: 87.90 ± 4.11 kg). The TRAINED group included four defensive backs, two wide receivers and 1 tail back who all followed a structured strength and conditioning program on average 14.7 hours per week, participating mainly in vigorous intensity (7.9 hours per week) weight lifting for power and speed, following active warm-up with flexibility and cardiovascular training. The TRAINED group did 6.8 hours a week of moderate activity. Seven healthy males with lower levels of physical activity (age, 23.00 ± 4.16 years; height, 1.73 ± 0.07 m; weight 73.27.0 ± 8.05 kg) were placed in the REC group. One source of exercise for the REC subjects' included moderate intensity activities through the enrolment in courses offered in the Physical Education and Activity Program at UTK (folkdance, walking, weight training), but also included recreational sport which totaled about 7.0 hours a week (3.6 hours per week of vigorous and 3.5 hours per week of moderate activity). In most cases three of these hours were through participation in their Physical Education classes. Prior to testing all subjects provided an informed consent as approved by the Institutional Review Board at the University of Tennessee**.**

Procedures

To assess physical activity levels and past training experiences, a Physical Activity Survey was administered. The Survey used some questions from the Behavioral Risk Factor Surveillance System Questionnaire (BRFSS) (1) with additional questions added about participation, frequency, intensity and duration of strength training other specific sporting activities performed during a typical week and injury history. Each participant attended two testing sessions. Each testing session began with a warm up of stationary biking or treadmill running as chosen by the participant and stretching.

Participants were also given the opportunity to practice each movement task 3 or 4 times prior to testing.

Isokinetic Strength Assessment

Strength of the dominant knee flexors and extensors were measured utilizing an isokinetic dynamometer, Biodex System 3, (Biodex Medical System, Shirley, New York, USA). The leg the participant would use to perform a single leg jump was deemed the dominant leg. Following the calibration of the dynamometer, the concentric and eccentric strength of knee flexors and extensors were measured according to the recommended procedures by the manufacturer. Concentric strength of knee flexion and extension was measured at $60° \cdot sec^{-1}$ and $180° \cdot sec^{-1}$, and eccentric strength at $60° \cdot sec^{-1}$. Five consecutive trials were performed at each angular velocity. A 90 second rest period was provided between all test conditions. The order of the angular velocities and contraction types testing was randomized. Flexion and extension peak torques (N·m/kg) were recorded by the device and were used for further analyses. All torque measurements were gravity corrected.

Biomechanical Testing

The second testing session began with height and weight measurements followed by warm up and maximum counter-movement vertical jump height testing using the Vertec standiometer (Sports Imports, Hilliard, OH). The maximum jump height for each participant was used to determine the actual height of drop landing height in the 100% maximal jump height (MJH) landing condition during data collection and for further analysis.

Kinematic and kinetic data were collected during the drop landing conditions. Each participant performed five landings from three different heights, (40, 60 cm and 100% MJH). The order of the testing movements was randomized by height. The drop landings were performed from an over-head horizontal bar controlled by an electrical hoist. Participants were asked to land with one foot on each of the two force platforms using a preferred normal landing technique.

Instrumentation and Data Analysis

Sixteen anatomical (1st and 5th metatarsal heads, medial and lateral maleoli, medial and lateral epicondyles, iliac crest, and greater trochanter) and 26 tracking (pelvis, thigh, shank, foot) markers were placed on both lower extremities during testing. A seven-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., UK) recorded three-dimensional (3D) position data. Two force platforms (1200 Hz, American Mechanical Technology Inc., Watertown, MA, USA) were synchronized to the motion capture system and measured the ground reaction forces. Only the data from the dominant leg were used for further analyses. All participants wore a pair of lab shoes (Adidas, USA) during the biomechanical testing session. The 3D kinematic variables were computed in Visual3D (C-Motion, Inc.) A customized computer program (Microsoft VisualBASIC 6.0) was used to determine critical events and compute additional variables from the Visual3D outputs. The 3D kinematic variables were computed using the X-Y-Z Cardan sequence and expressed using the right-hand rule.

Statistical Analyses

A two-tailed independent t-test was used to compare vertical jump height, relative peak torque values and 100% landing condition variables between TRAINED and REC (version 15.0.1, SPSS, SPSS Inc. Chicago). The strength measures were evaluated using a mixed-design 2 x 2 (group x speed) repeated measures analysis of variance (ANOVA). A 2 × 2 (group x height) mixed-design ANOVA tested the effect of group (TRAINED, REC) and landing height (40cm, 60cm) on vertical GRF and knee range of motion variables. An alpha level of $p < 0.05$ was selected to indicate statistical significance. An alpha level of p values between 0.05 and 0.10 was considered marginally significant and described as a ‘trend’. Pearson product correlation coefficients were used to determine the relationships between eccentric strength measurements and peak vertical GRF variables.

RESULTS

The Physical Activity Survey results showed that the TRAINED group (883.32 minutes/week) was two times more active than the REC group (422.45 minutes/week) through their involvement in a required strength and conditioning program for all football athletes. Independent sample t-tests of the physical characteristics of the participants revealed that the TRAINED participants had significantly greater height ($p = 0.028$) and weight ($p = 0.001$). The mean maximum jump height of the TRAINED group, 74.52 ± 4.06 cm, was significantly higher ($p< 0.001$) than the REC group 55.28 ± 7.12 cm.

For the isokinetic strength assessment (Figure 1), the TRAINED participants had significantly greater peak concentric torque for knee extension (p = 0.03 and p= 0.021 respectively) compared with the REC participants at angular velocities of 60 and 180°·sec^{-1}. There were no significant differences (p = 0.902) found between groups for peak eccentric torque for knee flexion.

For the REC participants, high and significant correlations (p = 0.047) were found between the time to first GRF peak in 60 cm drop landing and the peak eccentric knee torque and (r = 0.76) (Table 1). For the TRAINED participants, high and significant correlations (p = 0.002 and p = 0.004 respectively) were found between the peak eccentric knee torque and the time to first (r = 0.94) and second (r = 0.92) GRF peak during 60 cm drop landing (Table 1).

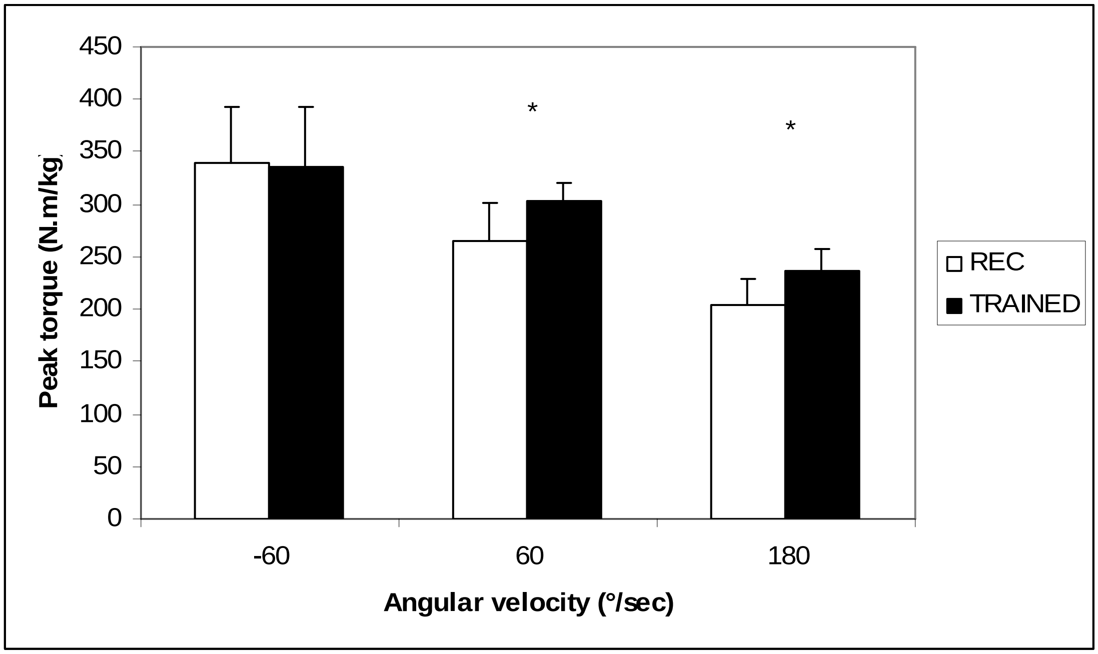

Figure 1. Relative peak torque developed by the REC and the TRAINED participants for knee extensors, from 60 ° · sec^{-1} eccentric to 180 ° · sec^{-1}concentric. Values are means (±SD).
* Significant difference between the TRAINED and the REC (p<0.05).

Table 1. Group correlations (*r*) between time to peak ground reaction force and peak torque.

Variable	Group	TF1 (40cm)	TF1 (60cm)	TF1 (100%)	TF2 (40cm)	TF2 (60cm)	TF2 (100%)
EPT60	TRAINED	0.68	0.94*	0.55	0.71	0.92*	0.36
EPT60	REC	0.61	0.76*	0.59	0.34	0.4	0.38

Note: 100% = maximum jump height landing,
EPT60 = eccentric knee extensor peak torque 60 ° · $\sec^{-1}$
TF1 = time to first peak GRF
TF2 time to second peak GRF
* Significant at $p<0.05$.

There was a significant height group interaction (p = 0.019) for the first GRF peak. The TRAINED and the REC groups were no different (p = 0.155) at 40 cm but were significantly different (p = 0.036) from each other at 60 cm with the TRAINED group having a significantly smaller first GRF peak .The first GRF peak for the TRAINED group was significantly lower (p = 0.036) than that of the REC group in drop landing from 60 cm (Table 2). As landing height increased from 40 to 60 cm the first GRF peak of both the REC and TRAINED groups increased significantly ($p < 0.001$). There was marginal significance (p = 0.051) in support of greater second GRF peak for the TRAINED subjects than the REC participants when landing from heights of 40 cm and 60cm (Table 2). The time to the second GRF peak for the TRAINED group was significantly less (p = 0.038) than the REC group in all drop landing conditions (40 cm, 60 cm). As landing height increased from 40 to 60 cm, the time to the second GRF peak of both the REC and TRAINED groups decreased significantly (p = 0.006) (Table 2).

Significant group differences were observed between the TRAINED and REC participants at the 100% level for the time to first ($p = 0.018$) and second ($p = 0.006$) GRF peaks and second GRF peak magnitude ($p = 0.003$). The TRAINED group had shorter times and greater peak GRF magnitude (Table 2).

Table 2. Mean peak vertical GRF variables in drop landing: mean ± SD.

Group	Height	F1$^{\#, a, *}$	TF1^{c}	F2^{a,c}	TF2^{a,b,c}
Rec	40cm	1.0±0.2	0.012±0.002	2.0±0.5	0.060±0.011
	60cm	1.7±0.3	0.011±0.002	2.7±0.8	0.053±0.011
Trained	40cm	0.8±0.2	0.009±0.003	2.7±0.6	0.048±0.011
	60cm	1.3±0.3	0.010±0.002	3.5±0.6	0.043±0.004
Rec	100%	1.6±0.4	0.012±0.002	2.7±0.7	0.054±0.010
Trained	100%	1.6±0.4	0.009±0.001	4.1±0.7	0.039±0.007

#: significant interaction between group and height
*: significant group difference at 60cm only
a: significant height difference from 40cm
b: significant group difference at both 40 and 60 cm
c: significant group difference at 100% landing height ($p<0.05$)

There were no significant differences found between groups for the knee angular measures for the sagittal plane for drop landing for the 40 and 60cm conditions (Table 3). The results showed a trend ($p = 0.057$) for REC participants utilizing more knee flexion during landing. Within both the TRAINED and the REC groups, the maximum knee flexion angle ($p = 0.002$), flexion range of motion ($p < 0.001$), contact velocity ($p = 0.006$) and maximum flexion velocity ($p < 0.001$) during landing increased significantly ($p<0.05$) from 40 to 60 cm during drop landing (Table 3). At the 100% landing condition there were significant ($p = 0.019$) group differences in maximum flexion velocity, with the TRAINED group having greater velocity. Although the TRAINED participants (75 cm) landed from much higher than the REC participants (55 cm) during the 100% drop land condition there was no significant difference in the amount of knee flexion (maximum flexion angle ($p = 0.794$) or flexion range of motion ($p = 0.757$) used during landing (Table 3).

Table 3. Mean knee flexion angular measures in drop landing: mean ± SD.

Group	Height	$Ang_{cont.}$	$MaxAng_{fl}^{a}$	ROM_{fl}^{a}	Vel_{cont}^{a}	$Max_{v.fl}^{a,c}$
Rec	40 cm	-28.7±5.7	-91.7±12.3	-62.7±10.5	-309.8±72.4	-518.2±66.9
	60 cm	-28.5±5.2	-98.1±11.7	-69.6±9.5	-347.0±65.9	-613.7±53.1
Trained	40 cm	-26.5±9.7	-80.8±13.3	-54.1±5.5	-271.4±35.3	-574.6±93.1
	60 cm	-24.7±9.9	-85.6±13.0	-60.7±5.8	-306.3±50.3	-656.2±81.4
Rec	100%	-27.4±5.1	-95.0±12.3	-67.6±9.7	-327.3±72.9	-619.7±73.1
Trained	100%	-26.8±9.0	-93.2±13.6	-66.3±5.5	-318.9±58.9	-733.4±83.4

Note: 100% = maximum jump height landing
Angle and ROM units: deg, Angular velocity units: deg · s^{-1},
$Ang_{cont.}$ = contact angle
$MaxAng_{fl}$ = maximum flexion
ROM_{fl} = flexion range of motion
Vel_{cont} = contact velocity
$Max_{v.fl}$ = peak angular velocity during flexion
a: significant height difference from 40cm
c: significant group difference at 100% landing height ($p<0.05$)

DISCUSSION

The purpose of this study was to investigate the relationship between vertical ground reaction force, knee kinematic variables during drop landing and concentric and eccentric torque generation of quadriceps muscles in TRAINED and REC collegiate participants. The TRAINED participants had a greater vertical jump height than the REC participants (Figure 1). According to the vertical jump norms for young adults (28) the TRAINED participants vertical jump height placed them in the 95th percentile (≥71.1 cm), while the REC participants (55 cm) were in the 45th percentile. Vertical jump performance is dependent on biomechanical factors such as the ability to generate muscular torque and speed of movement (15). Compared to the REC, the TRAINED participants demonstrated superior measures of concentric peak torque (Figure 1). Comparing our TRAINED and REC groups to percentile scores for concentric knee extensor peak torque at 60°/s of over 100 Australian Football League players the TRAINED group (3.03 NM/kg) ranked in the 80th percentile and the REC group (2.65 Nm/kg) ranked in the 40th percentile (37). These group differences in vertical jump and concentric strength may be a reflection of natural ability and training of the TRAINED participants compared to the REC participants. This is consistent with research that found TRAINED athletes, who participate regularly in sports requiring explosive actions or who train for power, have superior performance in tests of strength (4, 6, 18, 26, 31, 32, 35, 38). The TRAINED participants follow an intense, highly structured and supervised training schedule geared towards power generation, explosiveness and injury prevention, during which specific adaptations occur within the muscles (6, 9, 22). In the present study, the lower level of concentric knee extensor torque production of the REC participants might have influenced the vertical jump height, indicating that the

TRAINED participants have a greater ability to produce muscular torques that result in better jumping performance.

The results of concentric strength of the quadriceps, however, are of no indication of corresponding eccentric strength based on the results of this study. Although the TRAINED participants had greater concentric knee extension strength than the REC participants, possibly attributable to training differences, they demonstrated similar eccentric muscular capabilities in the current study (Figure 1). Little has been reported on eccentric knee flexor torque normative values. Our eccentric results were comparable to previous research results on soccer players, which found that professional players had significantly lower eccentric knee extensor peak torque than the amateur players and comparable concentric knee extensor strength (4). The eccentric peak torque developed by the knee extensors for both our TRAINED (336.3 Nm/kg) and REC (340 Nm/kg) participants were superior than Division 1 and Division 2 players, but were equal to the amateur players who demonstrated the higher eccentric values (4). The TRAINED group may not be any more eccentrically trained than our REC subjects, as the focus of the program they followed is geared towards increasing concentric strength and explosive power, through many Olympic lifts (snatch, hang, clean, power clean, squat, dead lifts) with heavy weight and less repetitions. They also engaged in sprint, agility and cardiovascular endurance training several days a week. Eccentric strength testing was new and challenging for both TRAINED and REC subjects. Both groups took longer to acclimatize to this isokinetic setting than the concentric testing mode, often having to practice several times prior to starting the test. However, the maximum torque value was taken from a series of 5 trials for all subjects and we did not observe any learning effect from the peak torque outputs.

Concentrically, the quadriceps muscle group plays an important role in explosive movements such as jumping (4). During landing, this muscle group plays an important role eccentrically in decelerating the body's vertical movement, controlling knee flexion, and maintaining joint stability, (7, 16, 20, 21, 24, 39). With comparable eccentric quadriceps strength, the TRAINED participants' ability to attenuate force through eccentric muscular contraction during landing is similar to the REC participants. To control the deceleration of the body through eccentric quadriceps mechanisms, the TRAINED participants did use a marginally stiffer landing strategy compared to the REC participants. In addition, they may have relied more heavily on their eccentric strength resulting in the strong correlation between the peak eccentric knee torque and the time to first (r = 0.94) and second (r = 0.92) GRF peak during 60 cm drop landing. The strength testing results from this study and that of Comettis' (4) are intriguing. Cometti offered no explanation for the greater lower eccentric strength of professional player versus amateurs. In our study the TRAINED participant's greater concentric strength was possibly related to their strength and conditioning program which focuses on concentric strength production and improvement. The TRAINED group might not have received eccentric training any differently from the REC group which resulted in similar eccentric strength. Therefore further investigation is warranted to further examine the effect of greater eccentric strength on impact attenuation during landing. To our knowledge our investigation is the first study to specifically examine the relationship of isokinetic knee strength, especially the eccentric strength, and biomechanical landing characteristics in TRAINED and REC participants.

It was hypothesized that the TRAINED participants would have lower peak GRF and greater knee ROM than the REC participants in drop landing. In theory, decreased knee stiffness allows more time for the dissipation of the impact forces and allows the musculature to absorb some of these forces (5, 20, 25, 39). It is interesting to note that the characteristics of the two vertical GRF peaks were different for the two participant groups in the landing activity. It has been demonstrated that training experience can result in changes in landing characteristics (2, 3, 8, 10, 18, 20, 23, 29, 34). The TRAINED participants showed a significantly lower first GRF peak at 60 cm compared to the REC participants (Table 2). The TRAINED participants' landing resulted in marginally greater second GRF peak and significantly shorter time to reach the peak from 40 and 60 cm. Significance was seen from the 100% landing height (Table 2). This suggests that the TRAINED subjects experience greater loading rates during the heel touchdown. The greater loading rate reduced the amount of time available for the quadriceps muscles to work eccentrically to attenuate the impact and resulted in a greater magnitude of impact forces when landing. It has been reported that active and healthy subjects responded to increased landing mechanical demand (landing height) with greater increases in the first GRF peak and smaller increases in the second GRF peak (39). However, we found, that the TRAINED participants had a trend for greater second GRF peak and less knee ROM than the REC participants when drop landing from the same heights. Well-trained and experienced athletes (basketball, volleyball, gymnasts, parachutists) generally have increased knee flexion (8, 20, 22, 34), and lowered peak vertical ground reaction forces (29, 34) in comparison to REC performers. With a larger sample size these marginal differences may reach significance. Our results are not in agreement with some of the findings in the literature. Anecdotally, in comparison to basketball players during games and practices, football players jump and land less often and the majority of their training is focused on concentric force production. Therefore landing with greater knee flexion and smaller second GRF peak may not be developed from their training.

The knee kinematic patterns for both the TRAINED and REC groups were not significantly different from 40 and 60 cm (Table 3). There was, however, the appearance that the REC participants used more knee flexion when landing from 40 and 60 cm heights. At the 100% landing height level estimated based upon their individual maximum vertical jump height, the TRAINED group's 75 cm landing height at the 100% level was significantly greater than the 55 cm landing height of the REC group. Despite the jump height difference TRAINED and REC participants only differed in maximum flexion velocity. However, their contact angle and velocity, maximum knee flexion and ROM were similar to those of the REC participants. These kinematic results further suggest that the TRAINED participants adopt a stiffer landing strategy compared to their REC counterparts. During the data collection, all subjects were instructed to land normally with sufficient knee flexion. Landing "normally" also meant the subjects landed balanced and were able to stabilize themselves on the force platforms with no additional movement. This is a task that is specific to the laboratory and may not be common in the field or sporting arena, as often times landing from a jump is immediately followed by another action. In theory, TRAINED subjects should be better and have more experience in following specific instructions with regards to movements, and it can be hypothesized that they would better at controlling the movement of their body, and perhaps their marginally stiffer landing technique emerged in an effort to insure a stable landing.

The knee kinematics coupled with the peak GRF results of the TRAINED group in this study indicate that this group of subjects elected to use the stiffer landing style to handle the similar loading at the two standardized heights (40 and 60 cm). This was further verified in the 100% landing height condition in which the TRAINED participants used a similar landing ROM and maximum flexion angle while landing from higher heights to handle greater impact loading with a greater 2nd GRF peak and a shorter loading time. Joint ROM and muscle action play a major role in reducing GRF peak forces during impact (5, 14, 21, 27). A stiffer landing strategy is often associated with greater peak GRF in landing (5, 7, 39). The TRAINED subject's stiffer landing style also seems to have two consequences, namely a smaller first GRF peak and a marginally greater second GRF peak and associated loading for participants with more training and greater athletic ability. This suggests that the TRAINED participants may have a greater tolerance level of impact loading without sustaining injury and are better "equipped" to handle greater loading. The stiffer landing strategy adopted by the elite group further indicate that the elite participants may have greater potential and capacity to attenuate and tolerate high impact loading.

The hypotheses regarding peak GRF and eccentric knee strength for the TRAINED subjects were not supported by the results. The TRAINED participants had no differences in eccentric strength, and a trend for greater second GRF peak and less knee ROM compared to the REC participants. This indicates a stiffer landing strategy that may be related to the training program of the TRAINED participants. Relatively few landing studies have used isokinetic strength to examine relationships between lower extremity strength and capacity of impact force attenuation in landing (12, 16). In both of these studies strength and landing comparisons were made between gender, rather then level of experience or leg strength. In this study it was not possible to determine whether the differences found in the various performance characteristics were due to experience in landing, adaptation to training or selection.

In summary, it has been reported that different demands in sports lead to differences in muscle strength. It appears the sporting demands placed on the TRAINED participants have resulted in the enhanced ability to perform concentric actions. Despite all their training, the results of this study did not find any significant differences in eccentric strength of the TRAINED participants. However, they adopted, a stiffer landing strategy suggesting a greater capacity to deal effectively with higher loading. It may be inferred that the TRAINED individuals elected a landing strategy that best suits their performance needs.

Clearly, eccentric strength must have relevance in the eccentric actions of landing. Therefore, more research into its role in impact attenuation in landing is warranted. Future research should involve studying the landing strategies of participants with significant differences in eccentric strength, which will provide more information on the roles of eccentric strength in impact attenuation and normative values of eccentric strength.

PRACTICAL APPLICATIONS

In many sports such as gymnastics, basketball, volleyball, soccer, football and athletics, athletes expose their bodies to high impact loading and eccentric muscular contractions during landing. The results from this study suggest that TRAINED athletes elect to land with a stiffer landing style that and results in greater impact loading and less attenuation during landing, which may place them at a greater risk of impact related injuries. The TRAINED subject’s lack of increase in eccentric strength compared to the REC subjects may be a point of concern for strength and conditioning coaches and related to the proposed increased vulnerability of this group of participants. Increased eccentric training should be recommended for this group of participants to improve this deficit.

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APPENDICES

APPENDIX A: INFORMED CONSENT

APPENDIX A
INFORMED CONSENT FORM

Student Investigator: Jeremy Steeves
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Introduction: You are invited to participate in a research study entitled, "Relationship between leg strength and performance during a drop jumping and landing in college-aged males". The purpose of this research project is to measure leg muscle strength and power and compare these values with the performance of landing and jumping movements. This consent form may contain words that you do not understand. Please ask for an explanation of any words or information that you do not clearly understand. Before agreeing to be in this study, it is important that you read and understand the following explanation of the procedures, risks, and benefits.

Testing Protocol and Duration

On day one, you will visit the Biomechanics/Sports Medicine Laboratory where you will be asked to read and sign this Informed Consent Statement before participating in the testing session. Following a demographic questionnaire about your age, activity level and injury history a measurement of your height and body weight will be taken. You will then be escorted to the Neyland-Thompson Athletic Training Room where the test session will begin with a standard warm-up on the stationary bike and stretching. You will the perform leg extension and flexion exercises using your dominant leg on the isokinetic dynamometer, which is a machine that measures leg strength. This device functions much like a seated leg curl or a leg extension machine in a fitness center, but it will control the speed at which you are extending and flexing your legs while you press against it as hard as you can. You will perform maximal trials of eccentric and concentric extension and flexion using your dominant leg at 3 speeds, with a 1-minute rest period between each trial. The total time involvement for day one of the study is less than 1 hour.

On day two, you will meet back at the Biomechanics/Sports Medicine Laboratory. Following a standard warm-up, you will perform a vertical jump test in which you will be instructed to jump as high as you can while touching the highest point on the vertical jump testing device that you are able to reach. You will perform this test 3 times and your highest jump will be recorded. You will then perform several landing tests in which you will be instructed to drop from 2 different hanging heights from a horizontal bar (70 and 100% of maximal jump height) and land on both feet. You will land from each height 5 times. The drop jump test will follow the landing conditions. For the drop jump you will step forward off each of two different height platforms (70% and 100% of maximal vertical jump) with your dominant foot, however instead of coming to a balanced position upon ground contact you will be instructed to quickly reverse your downward motion and to jump again as high as possible. You will be instructed to jump in an attempt to reach for the Vertec levers which will be set up at 95% of your pretest maximum vertical jump. During the testing, biomechanics instruments will be used to obtain measurements. Some of these instruments will be placed/fixed on your body. None of the instruments will impede your ability to engage in normal and effective motions during the test. If you have any further questions, interests or concerns about any instrumentation, please feel free to contact the investigator. The total time involvement for day two of the study is about one hour making the total time involvement in the entirety of this study about two hours.

Potential Risks
Risks associated with this study are minimal. The risks involved include possible muscle soreness or injuries resulting from the landing and jumping tests. To decrease the possibility of muscle soreness ample practice will be provided for both movements and sufficient warm up is also required for you prior to the testing. The investigator or a research assistant will be stationed close to you and provide assistance in case you lose balance during the landing conditions.

Emergency Medical Treatment
In the event of an injury, the University of Tennessee does not automatically reimburse participants for medical claims or other compensation. Should any injury occur during the course of testing, standard first aid procedures will be administered as necessary. At least one researcher with a basic knowledge of athletic training and/or first aid procedures will be present at each test session. If physical injury is suffered in the course of research, or for more information, please notify the investigators Jeremy Steeves (974-8768) or Dr. Songning Zhang (974-2091). If you have questions about your rights as a study participant, please contact Brenda Lawson at 974-3466.

Benefits of Participation
You will also be given a printout which will include your leg strength values outlining the differences in strength between your quadriceps and hamstrings muscles as well as your vertical jump test results.

Compensation
No compensation will be provided.

Voluntary Participation and Withdrawal
Your participation in this study is entirely voluntary and you may withdraw from this study at any point. If you withdraw from this study prior to completing your data collection, your data will be destroyed. It is your obligation to ask questions regarding any aspect of this study that you do not understand. You acknowledge that you have been offered the opportunity to have any questions answered.

Confidentiality
Your identity will be held in strict confidence through the use of a coded subject number during data collection, data analysis, and in all references made to the data, both during and after the study, and in the reporting of the results. Though it is the intention of the researchers to publish and present the results of this study, your identity will not be disclosed. The consent form containing your identity information will be destroyed three years after the completion of the

study. If you decide to withdraw from the study, your information sheet and consent form with your identity and injury history will be destroyed at the conclusion of the study.

Contact Information

If you have any questions at any time about the study you may contact the principal investigator, Jeremy Steeves at 974-8768. Questions about your rights as a participant can be addressed to Research Compliance Services in the Office of Research at the University of Tennessee at (865) 974-3466.

Consent

The testing has been explained fully to my satisfaction and I agree to participate as described. I have been given the opportunity to discuss all aspects of this study and to ask questions. Answers to such questions, if any, were satisfactory. I am eighteen years of age or older, in good health, am qualified for the study and freely give my informed consent to serve as a subject in this study. By signing this consent form, I have not given up any of my legal rights as a participant.

Subject's Name:	Signature:	Date:
________________________	___________________	__________________

Investigator's Signature:	Date:
___________________________	_____________________

Subject Number___________

(Please Print Clearly)

Participant initials___________

APPENDIX B
PHYSICAL ACTIVITY SURVEY
(MODIFIED FROM SECTION 17 of 2007 BRFSS QUESTIONAIRE)

APPENDIX B
PHYSICAL ACTIVITY SURVEY
(MODIFIED FROM SECTION 17 of 2007 BRFSS QUESTIONAIRE)

Please read:

We are interested in two types of physical activity – vigorous and moderate. Vigorous activities cause large increases in breathing or heart rate while moderate activities cause small increases in breathing or heart rate (check or fill in answer that applies)

Now, thinking about the moderate activities you do in a usual week, do you do moderate activities for at least 10 minutes at a time, such as brisk walking, bicycling, vacuuming, gardening, or anything else that causes some increase in breathing or heart rate?

___ Yes
___ No
___ Don’t know / Not sure
___ No answer

How many days per week do you do these moderate activities for at least 10 minutes at a time?

___ Days per week
___ Do not do any moderate physical activity for at least 10 minutes at a time
___ Don’t know / Not sure
___ No answer

On days when you do moderate activities for at least 10 minutes at a time, how much total time per day do you spend doing these activities?

__:___ Hours and minutes per day
___ Don’t know / Not sure
___ No answer

Now, thinking about the vigorous activities you do in a usual week, do you do vigorous activities for at least 10 minutes at a time, such as running, aerobics, heavy yard work, or anything else that causes large increases in breathing or heart rate?

___ Yes
___ No
___ Don’t know / Not sure
___ No answer

How many days per week do you do these vigorous activities for at least 10 minutes at a time?

___ Days per week
___ Do not do any vigorous physical activity for at least 10 minutes at a time
___ Don’t know / Not sure
___ No answer

On days when you do vigorous activities for at least 10 minutes at a time per day, how much total time do you spend doing these activities?

__:___Hours and minutes per day
___ Don’t know / Not sure

___ No answer

Have you experienced any of the following lower extremity injuries? (check all that apply)

ACL injury	___NO	___ Yes	Date:___________
Collateral ligament damage	___NO	___ Yes	Date:___________
Patella/patella tendon damage	___NO	___ Yes	Date:___________
Lower extremity fracture	___NO	___ Yes	Date:___________
Meniscus tear/cartilage damage	___NO	___ Yes	Date:___________
Surgery (specify)_________________	___NO	___ Yes	Date:___________

If YES, please describe the injury, and when it happened:

____

____

____

Have you injured your lower extremities within the last 12 months? (check all that apply)

Ankle	___NO	___ Yes	Date:_______
Knee	___NO	___ Yes	Date:_______
Hip	___NO	___ Yes	Date:_______
Muscles (specify)____________	___NO	___ Yes	Date:_______

If YES, please describe the injury, and when it happened:

____

____

How many days a week do you participate in lower body strength training exercises? (check one)

1___ 2___ 3___ 4___ 5___ 6___ 7___

On those days how many hours a day do you participate in lower body strength training exercises? (check one)

1___ 2___ 3___ 4___ 5___ 6___ 7___

Describe the type of lower body strength training you participate in (check all that apply)
Free Weights___ Weight Machines___ High Intensity___ Low Intensity___

Endurance based (higher repetitions/ lighter weight) ___
Strength based (lower repetitions/ heavier weight) ___

In high school did you participate in any sports or activities that involved jumping and landing and at what level? (Check all applied in the first column, and check one of the 2 levels for the sport)

Basketball ___	recreational ___	varsity ___
Volleyball ___	recreational ___	varsity ___
Football ___	recreational ___	varsity ___
Other (specify) ___	recreational ___	varsity ___

How many days a week during your involvement with these activities did you train or practice for these sports? (check one)
1___ 2___ 3___ 4___ 5___ 6___ 7___

At the University of Tennessee do you currently participate in any sports or activities that involve jumping and landing and at what level? (Check all applied in the first column, and check one of the 3 levels for the sport)

Basketball ___	recreational ___	Club___	University Team ___
Volleyball ___	recreational ___	Club___	University Team ___
Football ___	recreational ___	Club___	University Team ___
Other (specify) ___	recreational ___	Club___	University Team ___

How many days a week during your involvement with these activities would you train or practice for these sports? (check one)
1___ 2___ 3___ 4___ 5___ 6___ 7___

APPENDIX C: DEFINITIONS OF VARIABLES

APPENDIX C
DEFINITIONS OF VARIABLES

Isokinetics

CPT_{60}	Concentric quadriceps extension relative peak torque to bodyweight $60^\circ \cdot \mathrm{sec}^{-1}$
CPT_{180}	Concentric quadriceps extension relative peak torque to bodyweight $180^\circ \cdot \mathrm{sec}^{-1}$
EPT60	Eccentric quadriceps flexion relative peak torque to bodyweight $60^\circ \cdot \mathrm{sec}^{-1}$

Vertical Ground Reaction Forces

F1	First vertical ground reaction force peak
TF1	Time to first vertical ground reaction force peak
F2	Second vertical ground reaction force peak
TF2	Time to second vertical ground reaction force peak

Kinematics

$\mathrm{Ang}_{\mathrm{cont.}}$	Contact angle at ground contact
$\mathrm{MaxAng}_{\mathrm{fl}}$	Maximum flexion joint angle
$\mathrm{ROM}_{\mathrm{fl}}$	Flexion range of motion of joint
$\mathrm{Vel}_{\mathrm{cont}}$	Angular joint velocity at ground contact
$\mathrm{Max}_{\mathrm{v.fl}}$	Maximum angular joint velocity during flexion
$\mathrm{TMax}_{\mathrm{v.ex}}$	Time to maximum angular joint velocity during extension

APPENDIX D: DESCRIPTIVE CHARACTERISTICS AND LANDING HEIGHTS

APPENDIX D:
DISCRIPTIVE CHARACTERISTICS AND LANDING HEIGHTS

Group		Subject #	Age	Ht (m)	Wt (kg)	Landing Height for 100%
REC	1	1	27	1.83	74.55	63
	2	11	29	1.778	71.36	45
	3	16	19	1.778	69.55	56
	4	24	23	1.666	65.45	64
	5	25	19	1.62	70.18	55
	6	28	25	1.7018	71.36	56
	7	29	19	1.7526	90.45	48
	Mean		23	1.73	73.27	55.29
	SD		4.16	0.07	8.05	7.02
TRAINED	1	9	20	1.78	86.95	75
	2	10	21	1.79	86.36	80
	3	14	19	1.78	87.73	76
	4	17	21	1.84	80.64	71
	5	18	20	1.84	91.36	70
	6	19	19	1.81	93.64	79
	7	26	19	1.81	88.64	71
	Mean		19.86	1.81	87.9	74.57
	SD		0.9	0.03	4.11	4.04

Note: SD = standard deviation

APPENDIX E: VERTICAL JUMP AND ISOKINETIC STRENGTH DATA

APPENDIX E:
VERTICAL JUMP AND ISOKINETIC STRENGTH DATA

Group		Subject #	Vertical Jump	CPT$_{60}$	CPT$_{180}$	EPT$_{60}$
REC	1	1	63.15	241.5	214.5	303.8
	2	11	45.17	240.7	178.2	371.2
	3	16	55.83	327.6	239.3	371.9
	4	24	64.33	298.9	227.3	415
	5	25	54.85	229.9	173.6	338
	6	28	55.90	253.6	206.9	250.8
	7	29	47.70	265.7	184.9	329.3
	Mean		55.28	265.41	203.53	340.00
	SD		7.12	35.52	25.37	53.23
TRAINED	1	9	74.96	301.2	222.1	278.1
	2	10	80.23	316.6	233.4	264.5
	3	14	75.49	295.2	263.9	346.9
	4	17	70.80	318	258.5	380.5
	5	18	70.19	267.2	211.6	356.3
	6	19	79.00	299.8	251.9	309.4
	7	26	70.99	319.6	215.7	418.6
	Mean		74.52	302.51	236.73	336.33
	SD		4.06	18.44	21.37	55.54

Note: SD = standard deviation

APPENDIX F: INDIVIDUAL AND GROUP VERTICAL GROUND REACTION FORCE DATA FOR LANDING

APPENDIX F:
INDIVIDUAL AND GROUP VERTICAL GROUND REACTION FORCE DATA FOR LANDING: mean ± SD.

Group	Height	Subject	F1	T F1	F2	T F2
REC	40cm	1	0.78±0.10	0.012±0.001	1.69±0.23	0.075±0.004
		11	1.14±0.06	0.015±0.002	1.69±0.29	0.071±0.008
		16	0.73±0.09	0.013±0.003	1.60±0.10	0.064±0.012
		24	1.33±0.14	0.011±0.001	2.56±0.27	0.055±0.009
		25	0.98±0.04	0.012±0.001	1.68±0.24	0.058±0.006
		28	0.86±0.05	0.008±0.001	2.94±0.17	0.042±0.003
		29	1.11±0.10	0.011±0.001	2.13±0.29	0.058±0.004
		Mean±SD	0.99±0.21	0.012±0.002	2.04±0.53	0.060±0.011
TRAINED	40cm	9	0.76±0.10	0.005±0.003	2.82±0.18	0.032±0.012
		10	0.68±0.07	0.008±0.002	2.62±0.29	0.042±0.006
		14	0.90±0.07	0.013±0.002	1.96±0.71	0.065±0.011
		17	1.14±0.19	0.013±0.004	3.59±0.30	0.049±0.012
		18	0.83±0.06	0.008±0.001	3.15±0.67	0.047±0.004
		19	0.69±0.13	0.009±0.002	2.43±0.42	0.044±0.007
		26	0.85±0.18	0.011±0.004	2.23±0.47	0.059±0.019
		Mean±SD	0.84±0.16	0.009±0.003	2.68±0.56	0.048±0.011
REC	60cm	1	1.43±0.12	0.011±0.001	1.98±0.28	0.062±0.005
		11	1.97±0.09	0.013±0.002	2.01±0.27	0.066±0.008
		16	1.59±0.23	0.014±0.001	2.30±0.27	0.059±0.003
		24	2.19±0.14	0.012±0.001	3.14±0.51	0.048±0.004
		25	1.49±0.05	0.013±0.001	2.08±0.32	0.057±0.003
		28	1.53±0.20	0.007±0.002	3.92±0.53	0.038±0.004
		29	1.97±0.17	0.009±0.002	3.67±0.34	0.042±0.006
		Mean±SD	1.74±0.30	0.011±0.002	2.73±0.83	0.053±0.011

Continued

Group	Height	Subject	F1	T F1	F2	T F2
TRAINED	60cm	9	1.21±0.18	0.008±0.001	3.31±0.24	0.041±0.002
		10	0.98±0.06	0.008±0.001	3.81±0.34	0.036±0.004
		14	1.37±0.03	0.011±0.003	2.68±0.73	0.046±0.004
		17	1.99±0.28	0.012±0.001	4.07±0.34	0.046±0.004
		18	1.16±0.04	0.010±0.002	4.03±0.54	0.045±0.002
		19	1.12±0.34	0.010±0.001	3.59±0.34	0.039±0.003
		26	1.53±0.21	0.012±0.002	2.85±0.68	0.048±0.006
		Mean±SD	1.34±0.34	0.010±0.002	3.48±0.55	0.043±0.004
REC	100%	1	1.50±0.04	0.012±0.001	2.29±0.24	0.059±0.004
		11	1.41±0.07	0.015±0.002	1.96±0.18	0.067±0.007
		16	1.69±0.21	0.013±0.002	2.14±0.45	0.061±0.007
		24	2.42±0.10	0.011±0.002	3.33±0.50	0.046±0.004
		25	1.38±0.09	0.013±0.002	2.13±0.60	0.058±0.010
		28	1.53±0.13	0.008±0.002	3.69±0.35	0.040±0.002
		29	1.56±0.15	0.011±0.001	3.30±0.31	0.048±0.003
		Mean±SD	1.64±0.36	0.012±0.002	2.69±0.72	0.054±0.010
TRAINED	100%	9	1.75±0.20	0.010±0.002	3.34±0.26	0.045±0.005
		10	1.20±0.03	0.008±0.002	4.68±0.37	0.033±0.003
		14	1.82±0.12	0.010±0.002	3.16±0.54	0.047±0.006
		17	1.99±0.15	0.010±0.001	5.06±0.46	0.038±0.001
		18	1.30±0.04	0.008±0.002	4.07±0.38	0.042±0.002
		19	0.91±0.07	0.007±0.002	4.74±0.53	0.029±0.002
		26	2.09±0.27	0.011±0.002	3.85±0.95	0.043±0.006
		Mean±SD	1.58±0.44	0.009±0.001	4.13±0.73	0.039±0.007
Group Results						
REC	40cm		1.0±0.2	0.012±0.002	2.0±0.5	0.060±0.011
	60cm		1.7±0.3	0.011±0.002	2.7±0.8	0.053±0.011
TRAINED	40cm		0.8±0.2	0.009±0.003	2.7±0.6	0.048±0.011
	60cm		1.3±0.3	0.010±0.002	3.5±0.6	0.043±0.004
REC	100%		1.6±0.4	0.012±0.002	2.7±0.7	0.054±0.010
TRAINED	100%		1.6±0.4	0.009±0.001	4.1±0.7	0.039±0.007

APPENDIX G: INDIVIDUAL AND GROUP KNEE ANGULAR DATA IN LANDING

APPENDIX G
INDIVIDUAL AND GROUP KNEE ANGULAR DATA IN LANDING: mean ± SD.

Group	Sagital Plane (X)					
	Height	Subject	$Ang_{cont.}$	$MaxAng_{fl}$	$TMaxAng_{fl}$	ROM_{fl}
REC	40cm	1	-35.56±1.52	-94.65±4.58	0.25±0.01	-57.47±2.49
		11	-29.95±0.85	-84.21±5.28	0.27±0.01	-54.26±4.67
		16	-29.81±3.88	-113.59±5.73	0.38±0.04	-83.78±7.27
		24	-33.11±2.50	-92.22±5.24	0.25±0.05	-59.11±5.65
		25	-20.17±2.06	-83.70±5.56	0.24±0.06	-63.52±3.75
		28	-21.71±1.41	-75.43±4.81	0.20±0.02	-53.72±5.31
		29	-30.88±2.51	-98.11±2.77	0.27±0.02	-67.23±2.53
		Mean±SD	-28.74±5.71	-91.70±12.34	0.27±0.06	-62.73±10.47
TRAINED		9	-26.42±6.76	-82.84±4.53	0.17±0.02	-56.42±3.00
		10	-28.44±1.01	-90.55±3.85	0.23±0.02	-62.11±4.14
		14	-22.97±1.81	-80.21±6.18	0.24±0.01	-57.24±5.31
		17	-24.13±4.76	-77.91±5.59	0.20±0.02	-53.03±4.86
		18	-9.71±3.16	-54.10±2.06	0.58±1.02	-44.39±3.43
		19	-41.61±2.13	-95.94±7.43	0.26±0.06	-53.99±7.35
		26	-32.12±1.66	-84.12±5.18	0.46±0.11	-51.27±6.56
		Mean±SD	-26.49±9.69	-80.81±13.30	0.31±0.15	-54.06±5.52

REC	60cm	1	-35.87±2.44	-105.84±7.14	0.25±0.02	-69.53±5.38
		11	-27.79±2.16	-93.32±5.36	0.26±0.01	-65.53±5.14
		16	-28.34±1.56	-116.67±2.22	0.31±0.03	-88.32±2.34
		24	-30.14±1.61	-95.46±1.84	0.25±0.03	-65.33±2.36
		25	-22.20±0.88	-94.01±3.57	0.26±0.02	-71.82±3.39
		28	-22.05±0.71	-79.47±5.09	0.19±0.02	-57.41±4.92
		29	-32.97±3.57	-102.11±5.91	0.25±0.02	-69.13±5.97
		Mean±SD	-28.48±5.15	-98.12±11.65	0.25±0.04	-69.58±9.48

Continued

Group	Sagital Plane (X)					
	Height	Subject	$Ang_{cont.}$	$MaxAng_{fl}$	$TMaxAng_{fl}$	ROM_{fl}
TRAINED	60cm	9	-22.73±1.93	-85.19±2.79	0.19±0.01	-62.46±2.57
		10	-23.91±1.94	-84.40±4.60	0.20±0.03	-60.49±3.08
		14	-21.21±4.13	-89.76±5.23	0.25±0.02	-68.55±6.29
		17	-22.57±1.99	-84.30±5.94	0.21±0.03	-61.26±5.33
		18	-10.07±2.61	-64.44±5.05	0.12±0.01	-54.38±5.08
		19	-42.89±2.58	-108.62±8.11	0.33±0.05	-65.73±7.50
		26	-29.30±1.87	-82.67±1.43	0.34±0.13	-52.16±2.74
		Mean±SD	-24.67±9.90	-85.63±12.95	0.24±0.08	-60.72±5.82
REC	100%	1	-31.85±3.62	-100.57±7.20	0.24±0.01	-68.72±4.73
		11	-26.16±2.52	-85.26±5.26	0.280±0.02	-59.07±4.54
		16	-28.72±7.66	-115.65±4.63	0.30±0.02	-86.92±5.74
		24	-33.49±1.54	-102.83±3.12	0.23±0.02	-69.34±2.49
		25	-19.65±3.18	-87.43±5.10	0.22±0.03	-67.78±5.35
		28	-21.96±0.88	-79.84±5.61	0.19±0.02	-57.88±6.10
		29	-29.82±3.32	-93.63±7.31	0.24±0.01	-63.81±4.30
		Mean±SD	-27.38±5.10	-95.03±12.27	0.24±0.04	-67.64±9.66
TRAINED		9	-22.26±0.67	-87.85±1.16	0.20±0.01	-65.59±1.01
		10	-29.47±2.20	-97.95±5.11	0.24±0.03	-68.48±6.76
		14	-26.74±1.97	-97.01±4.57	0.26±0.02	-70.27±3.24
		17	-23.42±2.00	-83.80±3.75	0.24±0.05	-60.33±5.25
		18	-13.36±1.94	-75.88±6.13	0.21±0.01	-61.77±4.75
		19	-42.92±1.67	-118.65±2.93	0.36±0.02	-75.73±3.24
		26	-29.10±3.17	-91.13±5.45	0.32±0.10	-62.02±5.59
		Mean±SD	-26.75±8.99	-93.18±13.58	0.26±0.06	-66.31±5.54
Group Results						
REC	40 cm		-28.7±5.7	-91.7±12.3	0.27±0.06	-62.7±10.5
	60 cm		-28.5±5.2	-98.1±11.7	0.25±0.04	-69.6±9.5
TRAINED	40 cm		-26.5±9.7	-80.8±13.3	0.31±0.15	-54.1±5.5
	60 cm		-24.7±9.9	-85.6±13.0	0.24±0.08	-60.7±5.8
REC	100%		-27.4±5.1	-95.0±12.3	0.24±0.04	-67.6±9.7
TRAINED	100%		-26.8±9.0	-93.2±13.6	0.26±0.06	-66.3±5.5

APPENDIX H: INDIVIDUAL AND GROUP KNEE ANGULAR VELOCITY DATA IN LANDING

APPENDIX H:
INDIVIDUAL AND GROUP KNEE ANGULAR VELOCITY DATA IN LANDING: mean ± SD

Group	Sagital Plane (X)				
	Height	Subject	Vel_{cont}	$\text{Max}_{v.fl}$	$\text{TMax}_{v.fl}$
REC	40cm	1	-328.60±25.95	-487.32±37.56	0.10±0.01
		11	-225.77±9.81	-407.31±52.43	0.09±0.01
		16	-392.83±31.19	-568.22±21.35	0.05±0.02
		24	-217.73±25.24	-512.31±58.44	0.07±0.01
		25	-401.74±22.88	-564.50±33.58	0.03±0.00
		28	-294.24±19.79	-605.44±32.76	0.05±0.01
		29	-307.93±23.80	-482.51±16.16	0.05±0.02
		Mean±SD	-309.83±72.44	-518.23±66.85	0.06±0.03
TRAINED		9	-288.19±15.49	-679.95±32.66	0.05±0.02
		10	-249.05±19.12	-679.30±28.28	0.06±0.01
		14	-336.35±65.43	-487.96±42.01	0.04±0.02
		17	-261.07±28.90	-612.13±29.99	0.07±0.01
		18	-266.89±36.46	-553.28±54.91	0.07±0.01
		19	-222.98±35.15	-578.06±40.00	0.07±0.01
		26	-275.16±30.16	-431.30±62.04	0.06±0.02
		Mean±SD	-271.39±35.32	-574.57±93.07	0.06±0.01

REC	60cm	1	-368.85±34.35	-610.97±28.95	0.09±0.01
		11	-307.25±33.77	-512.11±44.21	0.07±0.02
		16	-399.85±44.42	-632.49±31.44	0.05±0.03
		24	-258.14±43.96	-614.72±29.37	0.05±0.02
		25	-446.93±35.44	-627.88±11.13	0.03±0.00
		28	-357.61±20.73	-690.92±27.61	0.05±0.00
		29	-290.48±22.57	-606.55±39.95	0.06±0.01
		Mean±SD	-347.01±65.88	-613.66±53.07	0.06±0.02

Continued

Group	Sagital Plane (X)				
	Height	Subject	Vel_{cont}	$\text{Max}_{\text{v.fl}}$	$\text{TMax}_{\text{v.fl}}$
TRAINED	60cm	9	-282.22±28.05	-713.63±35.20	0.06±0.01
		10	-352.28±24.08	-748.70±49.89	0.05±0.01
		14	-338.53±51.47	-627.71±70.47	0.06±0.02
		17	-350.09±37.32	-697.01±52.46	0.07±0.00
		18	-302.29±34.59	-673.40±30.05	0.06±0.00
		19	-208.76±20.95	-633.59±22.51	0.06±0.01
		26	-310.17±44.75	-499.42±29.64	0.05±0.02
		Mean±SD	-306.33±50.32	-656.21±81.36	0.06±0.01
REC	100%	1	-352.92±22.06	-631.34±38.86	0.08±0.01
		11	-249.25±29.96	-485.99±49.06	0.09±0.01
		16	-389.06±37.79	-659.92±76.58	0.05±0.03
		24	-252.23±24.58	-669.50±34.18	0.06±0.01
		25	-439.27±21.27	-647.33±56.56	0.04±0.02
		28	-336.40±20.84	-689.38±13.66	0.05±0.00
		29	-272.17±26.04	-554.23±38.60	0.06±0.01
		Mean±SD	-327.33±72.87	-619.67±73.05	0.06±0.02
TRAINED		9	-302.82±15.21	-709.68±47.09	0.06±0.01
		10	-306.15±22.71	-834.62±18.48	0.05±0.00
		14	-434.59±49.28	-615.30±42.56	0.06±0.01
		17	-321.89±59.10	-794.08±37.60	0.06±0.00
		18	-341.00±32.95	-764.71±44.30	0.06±0.00
		19	-252.17±38.69	-781.80±26.52	0.05±0.00
		26	-273.65±40.36	-633.46±34.65	0.06±0.01
		Mean±SD	-318.89±58.88	-733.38±83.42	0.06±0.01
Group Results					
REC	40 cm		-309.83±72.44	-518.23±66.85	0.06±0.03
	60 cm		-347.01±65.88	-613.66±53.07	0.06±0.02
TRAINED	40 cm		-271.39±35.32	-574.57±93.07	0.06±0.01
	60 cm		-306.33±50.32	-656.21±81.36	0.06±0.01
REC	100%		-327.33±72.87	-619.67±73.05	0.06±0.02
TRAINED	100%		-318.89±58.88	-733.38±83.42	0.06±0.01

VITA

Jeremy Steeves was born in Riverview, New Brunswick, Canada, on May 24, 1983. He graduated from Riverview High School, where he was graduate class president in June, 2001. Jeremy attended St. Francis Xavier University in Antigonish, Nova Scotia, where he received a Bachelor of Science degree in Human Kinetics in May, 2005. During his four years of undergraduate study, Jeremy was a member of St. Francis Xavier's Men's Varsity Football team. While competing at the collegiate level, Jeremy served as a team captain and received National Rookie of the Year and All-Canadian honors. Upon completion of his undergraduate degree, Jeremy was drafted 32nd overall in to the Canadian Football League only to be injured during training camp. Jeremy returned to St. Francis Xavier University to recover and play one final University season with hopes of returning to the CFL the following year. Another serious injury changed Jeremy's plans and he was forced to return home to Riverview where he filled a teaching position at a local high school. Realizing a desire to continue his education, Jeremy began the search for an institution for the pursuit of a graduate degree. His love of sports and his passion for working with athletes lead him to seek a degree in Biomechanics.

Jeremy entered graduate school at the University of Tennessee, Knoxville in 2006 to study Biomechanics. During his first year of graduate studies, Jeremy taught undergraduate classes in the university's Physical Education Activity Program. Jeremy took advantage of a once in a lifetime opportunity at a chance to play professional football and made the decision to leave the University of Tennessee following his first year to pursue a football career with the Edmonton Eskimo's Football Club in the Canadian Football League. Unfortunately, more than half way through his first season

Jeremy was released for the team and returned to Tennessee to complete his degree. In 2008, Jeremy will graduate with a Master of Science degree with a concentration in Biomechanics and continue his studies in the doctoral program in Exercise Physiology at the University of Tennessee, Knoxville.