12-2013

Biomechanical Difference between Chronic Ankle Instability Individuals and Healthy Individuals during Landing on Flat, Inverted and Combined Surfaces

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To the Graduate Council:

I am submitting herewith a thesis written by Xuan Liu entitled "Biomechanical Difference between Chronic Ankle Instability Individuals and Healthy Individuals during Landing on Flat, Inverted and Combined Surfaces." 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 Kinesiology.

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Biomechanical Difference between Chronic Ankle Instability Individuals and Healthy Individuals during Landing on Flat, Inverted and Combined Surfaces

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

Xuan Liu

December 2013

ACKNOWLEDGEMENTS

I would like to thank my major advisor, Dr. Songning Zhang, for giving me opportunities and helping me through this process. I would also like to thank Dr. Clare Milner and Dr. Coe for serving on my committee and giving me valuable input and encouragement. Thank Hairui Liu, Jake Gardener, Ying Fang, Chen Wen, and Tyler Standifird for your help in data collection and processing. I would also thank my family and friends for their continued belief and support. I cannot do the work without all of you.

Abstract

Lateral ankle sprains most frequently occurs during sports. Individuals who experienced a first time ankle sprain had a high reoccurrence rate and residual symptoms and functional instability leading to chronic ankle instability (CAI). The purpose of this study was to investigate kinematic and kinetic differences between CAI individuals and healthy subjects in single-leg drop landing on a flat surface, an inverted surface and a combined surface of inversion and plantarflexion. A total of 17 subjects (6 subjects with chronic ankle instability, 11 healthy subjects) performed five trails in each of four dynamic movement conditions of drop landing from a height of 30 cm onto a force plat form: double leg landing, single-leg drop landing on flat surface, inversion surface of 25 degrees and combined surfaces of 25 degrees of inversion and 25 degrees of plantarflexion. A nine-camera motion analysis system was used to capture the movement of dynamic testing. A 2 × 4 (ankle stability × surfaces) repeated measures ANOVA was used to evaluate the variables for dynamic testing ($p<0.05$). The results showed that single-leg landing on inverted surface resulted in significantly greater peak inversion, peak inversion ROM and peak eversion moment. Greater peak lateral GRF, shorter time to peak lateral GRF, and peak vertical GRF and its loading rate coupled in single-leg landing on combined surface were found compared to landing on inverted surface. These results may suggest single-leg landing on combined surface may be even more challenging and more suitable than inverted surface as a testing protocol in investigating lateral ankle sprain related issues.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

CHAPTER I
INTRODUCTION

Lateral ankle sprains mostly occurred during sports (27, 40). It was reported that ankle was the most frequent injured site among 70 sports and ankle sprain was the most common injury in 33 sports out of 43 sports (27). The National Collegiate Athletic Association (NCAA) injury surveillance data from 1988 to 2004 also demonstrated that ankle ligament sprains occurred more frequently in men's basketball, women's basketball, women's gymnastics, men's soccer, women's soccer, and men's spring football (40).

The most common ankle injury mechanism is excessive inversion when ankle is in plantarflexion (27, 28, 40). It usually occurs during an abnormal lateral cutting or landing on uneven surface (28). Results from a simulation study (68) showed that increased plantarflexion angle at touchdown caused an increase in peak passive inversion moment and peak inversion angle and therefore increased occurrence of potential ankle sprains. It has also been demonstrated that individuals who experienced a first time ankle injury had a 73.5% reoccurrence rate and 59% of them had residual symptoms and functional instability (70), which are the major factors leading to chronic ankle instability (CAI) (33).

A CAI model developed by Hertel (33) is widely accepted among CAI studies and suggested that mechanical instability and functional instability are a part of an instability continuum (33). Once both conditions of ankle instability are present, recurrent ankle sprain occurs. Hiller et al. (35) proposed a new CAI model developed from Hertel's original model (33). Compared to the three subgroups in the Hertel's model, the new model included seven subgroups The seven subgroups were mechanical instability, perceived instability (functional instability), combined mechanical instability and perceived instability (without recurrent sprain), combined mechanical instability, perceived instability and recurrent sprain, combined mechanical instability and recurrent sprain, combined perceived instability and recurrent sprain, and recurrent sprain only. Hiller et al. (35) was able to demonstrate with their CAI data that mechanical instability and recurrent sprain can exist either independently or co-exist with each other. Based this research, the 7-group model seems to be a more comprehensive model for CAI.

The most commonly used term to describe ankle instability were the presence or sensations of "giving way" and recurrent ankle sprains based on a review study (15). In addition, several surveys have been used in the literature to detect ankle instability including Cumberland Ankle Instability Tool (CAIT) (36), Ankle Joint Functional Assessment Tool (58), Foot and Ankle Instability Measure (10), Foot and Ankle Ability Measure Foot (51), Ankle Outcome Score (55), Foot and Ankle Disability Index (32) and Ankle Instability Instrument (10). It was demonstrated that the CAIT is a simple, valid and reliable measurement for functional ankle instability and have acceptable construct validity and internal reliability (36). A score of 27.5 on CAIT is considered as the cut-off score for ankle instability and showed a good sensitivity, specificity and test-retest reliability (36). Instrumented arthrometry, stress x-ray and/or manual test should be utilized to assess ankle mechanical instability (15). A previous study showed that anterior drawer and talar tilt tests are two of the most commonly used manual tests for assessment of ankle mechanical instability and can be utilized to examine the integrity of ligaments (42). Hiller et al. (35) modified a 5-point scale (18) to create a 4-point scale of 0 to 3 (0=hypomibile, 1=normal, 2= moderate laxity, 3= severe laxity) in order to quantify ankle mechanical instability (37, 38).

In examination of performance characteristics of CAI subjects in dynamic movements, researchers usually used three testing protocols: inversion drop (12, 24, 26, 73), drop landing and step-off landing on inverted surface (12, 20, 30, 31, 64). In addition, the trapdoor platform with a certain degree of inversion (20˚, 25˚, or 30˚) was used to investigate effectiveness of ankle braces (12, 73). Inversion drop only introduces ankle inversion during a sudden release while landing on inverted surface may better simulate the actual ankle sprains during landing on uneven surface. Thus, landing on inverted surface probably is a more appropriate and demanding for investigating lateral ankle sprain related mechanisms and effects of ankle braces (12).

There are a few studies of landing on inverted surface. Gutierrez et al. (30) asked subjects to perform double-leg landing from a 30 cm platform with the test limb on to an inverted surface of 25˚ to simulate lateral ankle sprain. Significantly increased peak ankle plantarflexion (5˚), adduction (8˚) and inversion (4.5˚) were observed during inversion landing compared to landing on an even surface. In one study of 24 healthy college students, subjects performed single-leg drop landing on to a 20˚ inversion surface with and without an ankle brace (64) and found increased ankle eversion moment, indicating that either the brace generates great eversion moment to resist the inversion stress or increased muscle activation to increase the eversion torque. Very few studies of drop landing on the combined surface were found in the literature (5). Twelve recreational and healthy athletes did double-leg drop landing from an overhead bar of 30 cm onto a flat surface, an inversion surface of 25˚ and a combined surface of 25˚ inversion and 25˚ plantarflexion (5). The greater peak ankle inversion angle and peak inversion velocity but a smaller dorsiflexion were found for landing on the inverted and combined surface compared to the flat surface. In addition, increased peak dorsiflexion angle was observed during inverted surface landing compared to combined surface landing (5).

There were some differences between CAI subjects and healthy controls during landing. Greater loading rate of anterior and lateral GRF were found in recreational athletes with functional instability during stop jump and drop landing onto inverted surface compared to healthy controls (11). However, it was shown that there were no differences in the inversion, eversion ROMs, peak vertical GRFs, and peak medial GRF between functional instability and healthy subjects during drop landing on flat surface (75). In the study by Gutierrez et al. (30), all subjects were asked to perform double-leg landing from a platform with a height of 30 cm with the test limb on the inverted surface of 25˚ to simulate lateral ankle sprain. No differences were found in ankle laxity measurements from an instrumented arthrometer. No significant differences among CAI, copers and healthy subjects were found for inversion and plantar flexion angle at touchdown, maximum ankle plantar flexion, adduction, and inversion angles after touchdown. The authors attributed this lack of difference to large variability in the data and suggested that both hypomobile and hypermobile subjects were included in all three subject groups (30). Functional instability subjects performed differently from mechanical instability subjects. The mechanical instability group had greater dorsiflexion at touch-down and maximum eversion and small range of motion in sagittal plane during stop jump, and greater hip flexion ROM during stop jump compared to functional instability subjects (8, 9). No joint kinetic variables were reported about CAI subjects during landing on inversion surfaces in the literature.

Statement of Problem

Most studies only focused kinematics and adopted flat drop landing and inversion drop landing. Few studies adopted inversion drop landing. In addition, the investigators of previous study did not usually differentiate mechanical and functional instability. Therefore, the purpose of this study was to investigate kinematic and kinetic differences between CAI individuals with both functional and mechanical instability and healthy subjects in single-leg drop landing on a flat surface, an inverted surface and a combined surface of inversion and plantarflexion.

Hypothesis

The main hypothesis was that CAI individuals would have greater peak lateral GRFs, loading rate of vertical and lateral GRF, ankle contact front-plane angle, maximum inversion, inversion ROM, contact plantarflexion angle, and peak eversion. The secondary hypothesis of the current study are that peak mediolateral GRF, peak inversion, peak inversion ROM, peak eversion moment would be greater in landing on inverted surface compared to flat surface; and there would be greater peak inversion and dorsiflexion in landing on inverted surface compared to combined surface.

Delimitations

1. Healthy subjects and chronic ankle instability subjects were selected from a convenience sample of students on the campus of the University of Tennessee, Knoxville. Healthy subjects were free from major lower extremity injuries. Chronic ankle instability subjects had a scored above 28 of Cumberland Ankle Instability Tool and a scale of 2 or 3 for in the two manual tests: anterior drawer and talar tilt.
2. Each subject performed five trials in all three conditions.
3. GRF data were collected for 3 seconds unilaterally during each trail using force platforms at 1200 Hz. Kinematic data were collected by a nine-camera infrared motion capture system at 240 Hz.

Limitations

This study had the following limitations:

1. All tests were conducted in a laboratory setting.

2. All subjects had their own learning progress of drop landing on tilting surfaces.

3. The accuracy of the placement of skin markers on the bony landmarks may limit the accuracy of the 3D kinematics.

4. The accuracy of 3D kinematic systems and force platforms, and accuracy of marker placement limited the accuracy of kinematic and ground reaction force data.

Chapter II
LITERATURE REVIEW

Therefore, the purpose of this study was to investigate kinematic and kinetic differences between CAI individuals with both functional and mechanical instability and healthy subjects in single-leg drop landing on a flat surface, an inverted surface and a combined surface of inversion and plantarflexion. The literature review included the following sections in this chapter: background, chronic ankle instability models, inclusion criteria and ankle instability surveys, manual testing, biomechanics studies of landing, and conclusion.

Background

Lateral ankle sprain is one of the most common sport-related injuries (27, 40). After reviewing 227 epidemiology studies from 1977 to 2005, Fong et al. (27) reported ankle ranked the top (24 sports, 34.3%) of body injured site among 70 sports, and ankle sprain was the most common injury in 33 sports out of 43 sports. It is also demonstrated that the incidence of ankle-injury and ankle-sprain was high in team sports such as rugby, soccer, volleyball, handball and basketball. Similarly, it was reported that ankle ligament sprains occurred most often based on the National Collegiate Athletic Association (NCAA) injury surveillance data from 1988 to 2004 (40). It was found that ankle ligament sprains occurred more often than other sports in men's basketball, women's basketball, women's gymnastics, men's soccer, women's soccer, and men's spring football. The ankle joint complex which links leg to the foot is made up of talocrural joint and subtalar joint The strong deltoid ligament complex prevents the ankle from eversion on the medial side, while the ligament complex on the lateral ankle including anterior talofibular ligament (ATFL), calcaneofibular ligament (CFL) and posterior talofibular ligament (PTFL) provides resistance to inversion (66). The anterior talofibular ligament (ATFL) is the first to be injured since it is the weakest of the lateral collateral ligament. The calcaneofibular ligament might be injured in more severe lateral ankle sprains (39).

A lateral cutting movement or landing on uneven surface is a common mechanism leading to lateral ankle sprains (28). Abnormal cutting and landing on a slant surface can lead to an excessive inversion moment, which overload and damage the ATFL and CFL (68). The most common mechanism for lateral ankle sprains is excessive inversion when ankle is in plantar-flexion (27, 40). Wright and the co-workers (68) found that greater plantar flexion angle at touchdown when there was an increased incidence of inversion. Thus, they considered that greater plantar flexion at touchdown might result in increased occurrence of potential ankle sprains (68). It is demonstrated that individuals who experienced a first time ankle injury had a 73.5% reoccurrence rate and 59% of them had residual symptoms such as episode of giving way, pain, recurrent sprains and functional instability such as decreased physical activity level (70),which are the major factors leading to chronic ankle instability (CAI) (33).

Chronic Ankle Instability Models

Chronic Ankle Instability (CAI) is commonly related to two potential causes, mechanical instability and functional instability. A CAI model developed by Hertel (33) is widely accepted among CAI studies. In this model (33), mechanical instability (FI) and functional instability (MI) are part of a continuum (Figure 1). Functional instability may result from a lack of proprioception, neuromuscular-recruitment, postural control and strength. Mechanical instability may result from changed anatomic mechanics after the first ankle sprain consisting of pathologic laxity, abnormal arthrokinematics and synovial and degenerative changes. When both conditions of ankle instability are present, recurrent ankle sprain occurs.

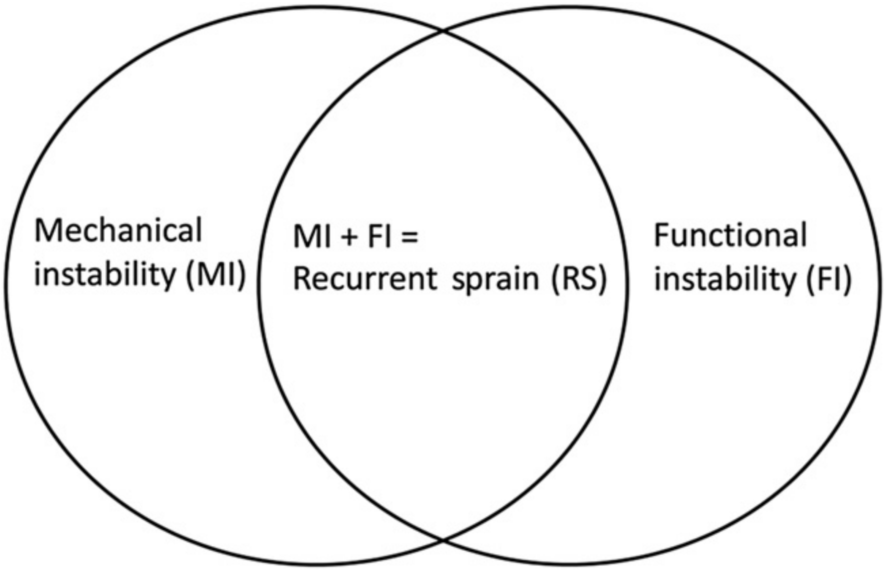


Figure 1. Hertel's CAI Model (33) .

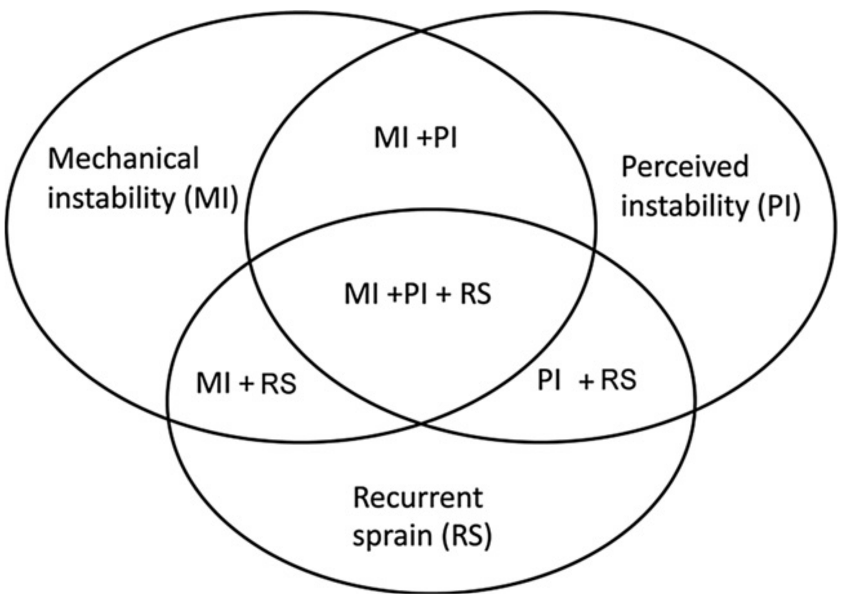


Figure 2. Hiller's Modified CAI Model (35)

Hiller et al. contemplated a new model developed from Hertel's CAI model (71). Compared to the three subgroups of Hertel's model, there were seven subgroups in this new model since perceived instability (instead of functional instability), mechanical instability and recurrent sprain can exist either independently or co-exist with each other (Figure 2). The seven groups are as follow: mechanical instability, perceived instability, mechanical instability and perceived instability (without recurrent sprain), mechanical instability and perceived instability and recurrent sprain, mechanical instability and recurrent sprain, perceived instability and recurrent sprain, recurrent sprain. Using data of 108 CAI ankles from two studies (37, 38), only 61 ankles (56.5%) could be fitted to the Hertel's model. Those subjects who had both mechanical and functional instability but did not have recurrent sprain and who merely had recurrent sprains but without either or both types of instability could not be classified into the Hertel's model. The percentage of the subgroups are 42.6% for perceived instability, 30.5% for perceived instability and recurrent sprain, 11.1% for perceived and mechanical instability and recurrent sprain, 9.3% for mechanical and perceived instability. All of the data from those two studies could be now fitted into the new proposed model.

Inclusion Criteria and Ankle Instability Surveys

There are an increasing number of studies about chronic ankle instability. However, the results are inconsistent and varied greatly (71). A recent review indicated that the most commonly used term to describe ankle instability were the presence or sensations of "giving way" and recurrent ankle sprains (15). Nevertheless, there is no agreement about what composes ankle joint "giving way" and "feelings of instability". Thus (15), in order to recruit more homogenous subjects, an ankle instability survey should be used to differentiate CAI individuals and healthy controls by quantification of ankle instability. Several surveys have been used in the literature to detect ankle instability including Cumberland Ankle Instability Tool (CAIT) (36), Ankle Joint Functional Assessment Tool (AJFT) (58), Foot and Ankle Instability Measure (FAIM) (10), Foot and Ankle Ability Measure Foot (FAAM) (51), Ankle Outcome Score (FAOS) (55), Foot and Ankle Disability Index (FADI) (32) and Ankle Instability Instrument (AII) (21). Ankle Instability Instrument was shown high test-retest reliability for self-reporting of ankle instability (21), but all questions were answered by "yes" and "no", with no certain scores for ankle instability, it is not easy to define ankle instability. The AFJT was demonstrated a good assessment tool for ankle instability discrimination and the cut off score between functional instability group and normal people was 26 points (57). A review showed the AJFAT, the FAOS, the FADI and the FAMM had good inter-rater reliability and the FAOS, the FADI and the FAMM had good test-retest reliability. Among those four assessments, only the FAOS and the FAAM was demonstrated content validity and construct validity and none of them showed internal consistency (25). However, the FAOS, the FAMM and the FADI did not have a cut-off score (32, 51, 57). In Hiller's study, CAIT was demonstrated to be a simple, valid and reliable measurement for functional ankle instability (36). Concurrent validity was tested by comparison with the Lower Extremity Functional Scale (LEFS) and a 10-cm visual analog scale (VAS), construct validity and internal reliability were examined by Rasch analysis with goodness-of-fit, Youden index was used for testing discriminative validity, sensitivity and specificity. Intraclass correlation coefficient was used for test-retest reliability. The results showed CAIT significantly correlated to LEFS and VAS. Acceptable construct validity and internal reliability were showed for CAIT. 27.5 were the cut-off score of CAIT and good sensitivity, specificity and test-retest reliability were demonstrated (36).

Instrumented arthrometry, stress x-ray and/or manual test should be utilized to assess the presence or absence of mechanical ankle instability (15). Besides two inclusion criteria above, Delahunt et al. (15) suggested that additional information should be included in the inclusion criteria, such as the number of previous ankle sprains, time since last diagnosed sprain, presence/frequency of "giving way" episode, presence/frequency of feelings of ankle joint instability, number/frequency of feelings of ankle joint instability, number/frequency of previous ankle sprains, presence of pain during activities of daily living or sporting participation, history of other injuries particularly at the time of sprain, assessment tool scores, activity profile (e.g., sporting level, recent activity level, etc.), nature of previous treatment, history of surgery or arthroscopic findings, insidious onset or history of trauma.

Manual Testing

In a review study, the relationship between MI and FI had not been established and MI subjects tended to be excluded when investigating FI (13). Functional instability assessments correlate with mechanical instability measures poorly (43, 67). In the study by Habbard et al. (43), 26 measurements were used to test mechanical and functional instability of ankle 30 CAI individuals, such as ankle arthrometer, posterior talar glide, postural stability, isokinetic ankle strength, isometric hip strength and Star Excursion Balance Test. The results of this study showed that both mechanical ankle instability measurements and functional ankle instability measurements were not totally dichotomous and should be done together. A more recent study by Wilkin and co-workers (67) demonstrated the Cumberland Ankle Instability Tool (CAIT) had a poor correlation with manual testing including anterior drawer test, talar tilt and inversion tilt, indicating that usage of questionnaire alone could not detect the mechanical instability of ankle joint. Therefore, elements of mechanical ankle instability and functional instability need to be measured together.

A previous study showed that anterior drawer and talar tilt tests are two of the most commonly used manual tests for assessment of mechanical ankle instability and can be utilized to examine the ligaments after a lateral ankle sprain (42). Lentell and co-workers (48) examined ligament laxity in 34 unilateral FI subjects by stress radiography. Greater talar tilt angles were found in functionally unstable ankle compared to contralateral stable ankle. Hertal et al. (34) investigated the ankle laxity between CAI and healthy subjects using anterior drawer and talar tilt. Significant greater laxity with anterior drawer test was found for CAI compared to the healthy subjects. It also showed good agreement between physical examination and fluoroscopic images. In this study, the first examiner used manual anterior drawer and talar tilt tests to measure the laxity of ankle joint in a four-point scale for people with and without ankle injury. The second tester measured the ankle laxity for the same group of people using the stress fluoroscopy with and without a manually applied supination stress. Among the subjects who were demonstrated excessive talar tilt by fluoroscopy, 78% of them also showed exaggerated ankle joint laxity in the anterior drawer test and 67% indicated laxity in the talar tilt test. In a recent review of 84 articles about lateral and syndesmotic ankle sprain injuries, it is reported that the anterior drawer test was used to test the anterior joint capsule and ATFL, which is the weakest one among lateral collateral ligament and the first to be injured (23). This ligament is used for stopping anterior translation of the talus and keeping ankle stable while talus internally rotates on the tibia (22). The calcaneofibular ligament prevents exaggerated ankle inversion by stabilizing talus and calcaneus. The talar tilt examines the integrity of calcaneofibular ligament (CFL), which is injured in more severe lateral ankle sprain, as well as the integrity of ATFL (23).

Ankle positions might be related to on the amount of ligamentous force experienced during manual testing. One study evaluated load-displacement relationships of 12 ankle specimens *in vitro* during an anterior drawer test at four different ankle positions, 10 degrees of dorsiflexion, neutral, and 10 degrees and 20 degrees of plantarflexion (62). Loading force was applied to the limit of ± 60 N on the intact ankle. The results indicated that the neutral zone laxity was increased the most at plantarflexion of 10˚ and 20˚ and flexibility was significantly greater at 10˚ of dorsiflexion compared to intact ankle. These results indicated that clinicians could detect the greatest neutral zone laxity between 10˚ and 20˚ of plantarflexion. Another *in vitro* study applied a 80 N anterior force during an anterior drawer test and 5.7 Nm of supination moment in the talar tilt test to an intact ankle, an ankle with AFTL sectioned and an ankle with both AFTL and CFL sectioned (2). All testings were done at the same four different angles (10 degrees dorsiflexion, neutral, and 10 degrees and 20 degrees plantarflexion). The results showed the ATFL force was the greatest at 20˚ plantarflexion and the CFL force was the greatest at 10˚ dorsiflexion for the intact ankle. No significant difference was found for the ankle laxity with ATFL cut. The laxity of ankle lack of ATFL was slightly increased. However, a significantly greater supination was found when both ligament were sectioned (2). In addition, an internal rotation of ankle was found after both ATFL and CFL were cut during the anterior drawer test. It was recommended that free internal rotation of the foot should be allowed during the anterior drawer testing. There were many studies about the ankle position in manual testing, but no consensus was reached.

Different scales of ankle joint laxity were used in studies on manual testing. The ankle laxity were measured using a 5-point scale: 1 - very hypomobile, 2 - slightly to moderately hypomobile, 3 - normal, 4 - slightly to moderately hypermobile, and 5 - very hypermobile (59).

Brown et al. (8) used this scale for manual testing in order to study the differences between the functional ankle instability and mechanical ankle instability groups. It was reported that testers' reliability was greater than 0.80 (0.25standard error) (61). Denegar and colleagues (17) estimated that greater laxity was found in subtalar and talocrural joint of injured ankles on a slightly different five-point scale (0=hypomobile, 1=normal, 2=mild laxity, 3= moderate laxity, and 4= gross laxity) derived from the Hertal's four-point scale (0= no laxity, 1= mild laxity, 2= moderate laxity, and 3= gross laxity) (34), where zero stands for no laxity. Hiller et al. (37) modified the 5-point scale (17) to create a 4-point scale of 0 to 3 (0=hypomibile, 1=normal, 2= moderate laxity, 3= severe laxity) in order to quantify ankle mechanical instability (37, 38) . Intrarater reliability of this method is excellent (3) .

In a recent study by Wilkin et al. (67), an eight-point scale from -2 for very stiff (hypomobility) to 5 for hypermobility was adopted . The scale was modified on the basis of the previous experience that a stiff ankle could be observed after a lateral ankle sprain (67). It was discussed that this 8-point scale may be too difficult to be used consistently in clinical settings. Therefore, the current study adopted the anterior drawer and talar tilt tests as tests of mechanical instability. The inter-rater reliability has been shown to be poor *in vivo* study after comparing test results among four experienced testers and one novice tester (67). Furthermore, personal sensitivity and experience of clinicians may further influence the results of manual testing. Blanshard and colleagues (6) found that the sensitivity of the anterior drawer test ranged from 32% to 80 %. Van Dijk et al. (63) showed the talar tilt test had a sensitivity of only 52%.

Biomechanical Studies of Landing

Normal Landing of Healthy Individuals

The studies on kinematics and kinetics of the lower extremity in landing have been focused on comparison of landing techniques (52, 60, 74), gender difference (65), effect of landing height (69, 74), and comparison of dominant leg and non-dominant leg (53). Kinematic s and kinetics are different using different landing techniques. A previous study has characterized soft or stiff landing techniques as the degree of peak knee flexion angles greater or less than 90 degrees (19). Greater peak GRFs were found with increased landing stiffness (74). In addition, decreased ROMs were reported along with the increased landing stiffness for both hip and knee joints. Furthermore, less eccentric work performed by hip and knee extensors was found with increased landing stiffness. Forty-eight males performed single-leg drop landing trials from an overhead bar at a height of 30.48 cm using four landing techniques: 1) natural landings, 2) landing with stiff knee and natural plantar flexors, 3) stiff landing with absorption by plantar flexors, and 4) stiff-landing absorbing most of the impact in the heels (60). Greatest peak GRF and peak tibial acceleration were reported in stiff-landing absorbing most of the impact in the heels compared to other three landing conditions.

In a study about gender differences, Huston and his colleague (44) reported there was significant gender difference of knee flexion at touchdown during drop landing from the height of 20, 40 and 60cm. Male subjects had a 16˚ of knee flexion, while the females subjects had a 7˚ of flexion angle, when they both landed from 60cm, which was the largest difference in knee flexion angle among three difference. When both men and women recreational athletes drop-landed from 60 cm, female exhibited greater maximal hip and knee flexion and ankle dorsiflexion (45). In another study, all the subjects (16 females, 17males) were required to perform double-leg landing and single-leg landing from a raised platform (65). Among the initial ground contact ankle, range of motion (ROM) and peak moments of three joints of lower extremity, the female subjects had a decreased hip flexion ROM and knee flexion ROM compared to the male subjects. In addition, a significant increase in plantarflexion at impact was found among women. Significantly greater peak ankle plantarflexion moment, less knee abduction and ankle inversion were observed during single-leg landing compared to double-leg landing for both genders. Additionally, increased ankle energy absorption was found in single-leg landing in comparison to double-leg landing, indicating ankle was used more in impact attenuation during single-leg landing for both genders.

Different landing height may influence biomechanical variables during landing. In double-leg step-off landings, the peak GRF, peak joint moments and powers of hip, knee and ankle were increased with increased landing height from 0.32 to 1.03 m for recreational athletes (74) . The eccentric work by ankle muscles also increased with the increased landing height. The peak GRF was also found elevated during double-leg step-off landing with increased landing height (0.15- 1.05m) (69).

The biomechanical difference between the dominant and non-dominant limb has been studied. Ankle joint angle, angular displacement and ankle joint angular velocity in all sagittal, frontal and transverse plane, peak GRF and time to peak GRF were calculated for the study of dominant-limb effect (53). Peak dorsiflexion and ankle abduction velocities were only found significantly increased for the dominant leg compared to the non-dominant limb.

In summary, greater GRF, decreased ROM of knee and hip, less work by knee and hip extensors were found in stiff-landing and landing from higher heights. Greater peak ankle plantar flexion moment, less knee abduction, ankle inversion, and increased ankle energy absorption was found in single-leg landing compared to double-leg landing. Peak dorsiflexion and ankle abduction angular velocities were greater in dominant leg. Females tend to have more variability at knee and hip during landing.

Influence of Inversion of Perturbation on Ankle Kinematics and Kinetics

Inversion Drop

With respect to the most common mechanism of lateral ankle sprains that excessive ankle inversion while ankle is in plantar flexion (27, 40) , researchers usually used three testing protocols with tilt platform to simulate the ankle sprain mechanism: inversion drop (12, 24, 26, 73) , drop landing on inverted surface (12, 64) and step-off landing on inverted surface (20, 30, 31).

A customized trapdoor inversion platform with a certain degree of inversion (20˚, 25˚, or 30˚) is typically used in inversion drop protocol (12, 24, 73). A sudden release of a tilting surface of the trapdoor platform initiates an ankle inversion motion. Some studies using inversion drop protocol focused on effectiveness of ankle brace (12, 73), while others investigated the lower extremity muscles activation during inversion drop (24). It was suggested that ankle dorsiflexion ROM (12), peak inversion angle and peak inversion ROM (73), peak inversion velocity and peak dorsiflexion velocity (26) were significantly decreased by wearing ankle brace during inversion drop. For the subjects with no brace, greater maximum inversion velocity was found in drop landing compared to inversion drop (12).

In addition to kinematic data, electromyographic (EMG) activities are also a common interest in inversion drop studies. The EMG of peroneal longus (PL) and tibialis anterior (TA) along with other ankle muscles are commonly collected because PL and TA are the two respective major everter and inverter of the ankle. The contraction of TA and PL influences stability of joints and ankle position pre-touch-down and post-touch-down (1) . It was also reported that the muscle latency response of PL and peroneus brevis (PB) was slower at higher plantar flexion angle. In the same study, faster plantar flexion angle led to faster latency response of TA, PL and PA during a sudden inversion drop (50).

Drop Landing on Inverted Surface

Among the previously published landing studies, there are a total of five studies about drop landing on an inverted surface. Three studies used drop landing from a platform of a certain height (20, 30, 31), the other two used drop landings from an overhead bar (12, 64). Two studies adopted single-leg landing protocol (20, 64). Only one study recruited subjects with unstable ankles (30) while other studies used healthy ankles (12, 20, 31, 64). Additionally, only one study adopted both unanticipated and anticipated condition (20).

A study about ankle instability subjects used the Cumberland Ankle Instrument Tool (CAIT) questionnaire to classify 45 subjects into the ankle instability group (history of ankle sprains and repeated episodes of "giving way", CAIT ≤ 28), lateral ankle sprain group (history of ankle sprain but without reported instability, CAIT≥ 28), and control group (no history of ankle sprain, CAIT >28) and (30). All subjects were asked to land from a platform with a height of 30 cm and land on both feet with the test limb on the inverted surface with 25˚ to simulate lateral ankle sprain. Significantly increased peak ankle plantarflexion (5˚on average), adduction (8˚on average) and inversion (4.5˚on average) were observed during inverted surface landing compared to landing on an even surface. Hagins et al. (31) found that in landing off a 40 cm platform onto slope with 3.6˚, 11.2 % body weight (BW) higher GRF in lateral direction was found compared to landing on a flat surface . A recent study focused on the differences between unanticipated and anticipated ankle inversion during drop landing (20). Twenty three healthy individuals were told to keep singe-leg stance on the non-tested leg until they were asked to perform landing with the tested leg on to the landing surface from a platform with a height of 20 cm. The landing surface changed randomly between a flat surface and an inverted surface with in inversion angle of 30˚. Greater peak vertical GRF, peak ankle inversion angle, inversion velocity and time from peak GRF to peak EMG were observed in unanticipated trials. In the unanticipated condition, subjects land faster, harder with more ankle inversion, which might increase the risk of ankle sprain (20).

Two studies investigated the effectiveness of prophylactic ankle bracing using drop landing (12, 64). In one study, 24 college students without any ankle or knee injury history performed single-leg drop landing on to a 20˚ inversion surface (64). Increased ankle eversion torque was shown in this study, indicating either brace generate great eversion torque to resist an inversion stress or increased muscle activation increase the eversion torque. In the study by Chen et al. (12),ankle inversion drop (25˚, 20cm) and drop landing onto an inverted surface (25˚, 45 cm) was compared in order to study the difference between two conditions and test effectiveness of ankle brace under those two conditions . During touchdown in inverted surface landing, there was a small inversion and plantar flexion, then peak inversion was achieved quickly. After that, a small eversion and relatively stable dorsiflexion were presented. Twelve physically active and healthy people participated in the study and showed that in inverted surface landing greater peak inversion velocity was found in inverted surface landing compared to inversion drop with and without brace landing by post hoc comparisons [P = 0.024; 95% confidence interval (CI), 17.6-197.0 degrees/second] (12). The ankle angular velocity during lateral ankle sprain might be associated with severity of injury (50). Significantly increased contact and maximum inversion velocity, reduced time to maximum inversion and inversion velocity found in inversion surface landing compared to the inversion drop, indicating landing on inverted surface is more demanding than inversion drop (12). Inversion drop only introduces ankle inversion during a sudden release. However, both ankle inversion and plantar flexion occur during lateral ankle sprains. Ankle is naturally at the position of plantar flexion during landing before initial contact. Additionally, landing on inverted surface from higher height simulates the actual ankle sprains during landing on uneven surface. Thus, landing on inverted surface probably is a more appropriate and demanding for investigating lateral ankle sprain related mechanisms and effects of ankle braces (12).

There are two studies simulating inversion combined with plantar flexion during inversion drop and drop landing (5, 24). Surface angle was provided in drop landing protocol only. Twelve recreational and healthy athletes did double-leg drop landing from an overhead bar of 30 cm onto a flat surface, an inversion surface of 25˚ and a combined surface of 25˚ inversion and 25˚ plantar flexion. The peak ankle inversion velocity and peak inversion angle of flat surface was lower than other two tilted surfaces. Greater ankle contact angle was found while landing on inverted surface compared to other two landing protocols. In addition, subjects exhibited increased peak dorsiflexion angle during inverted surface landing compared to combined surface landing (5). Eibig and co-workers (24) used inversion drop with a combined surface of plantar flexion and inversion. This study only focused on muscle activity, and no significant differences was found between EMG of peroneal and TA muscles in either unstable ankle group or stable ankle group.

Based upon the studies presented above, the landing height varies from 20 cm to 45 cm and the inversion angle varies from 3.6˚ to 25˚. The combined surface employs a 25˚ of inversion and a 25˚ of plantarflexion. Greater peak inversion angle, peak inversion velocity, peak ankle plantar flexion angle, ankle plantar flexion velocity, dorsiflexion angle, and peak dorsiflexion, peak ankle dorsiflexion angle were found on uneven surfaces.

Regular Landing of Chronic Ankle Instability Individuals

Differences between Functional instability and Healthy Controls

Several studies investigated the differences between ankle functional instability individuals and healthy controls. In a study with 15 unilateral functional ankle instable male basketball players and 17 matched healthy controls, significantly greater first peak vertical GRF and less time to the peak GRF were found for the functional instable ankle compared to the contralateral healthy ankle in a v-cut movement and functional instability subjects had a lower time to peak GRF (14). Lin et al. (49) found that recreational athletes with functional instability had a greater ankle inversion than healthy controls in 70% of the landing phase and a lower peak ankle eversion during a stop jump task, indicating functional instability subjects may have a higher risk of developing recurrent ankle sprain. In the study by Gutierrez et al. (30), all subjects were asked to perform double-leg landing from a platform with a height of 30 cm with the test limb on the inverted surface of 25˚ to simulate lateral ankle sprain. No differences were found in ankle laxity measurements (anterior displacement and stiffness, inversion rotation and stiffness, and eversion rotation and stiffness) from an instrumented arthrometer. No significant differences among CAI, coper and healthy subjects were found for inversion and plantar flexion angle at touchdown, maximum ankle plantar flexion, adduction, and inversion angles after touchdown. The authors attributed this lack of difference to large variability in the data and suggested that both hypomobile and hypermobile subjects were included in all three subject groups (30).

No kinematic differences in terms of frontal, sagittal or transverse plane motion or velocities of hip or knee were found between functional instability subjects and healthy controls during a 30cm lateral hop test from the edge of the force platform (16). The subjects with functional instability displayed lower posterior ground reaction force compared to the control group and their integrated EMG (IEMG) activity of rectus femoris, tibialis anterior and soleus are significantly greater during pre-initial contact (pre-IC) and post-initial contact (post-IC) (16). The study also showed that from 45ms pre-IC to 95ms post-IC, the functional instability individuals had a lower time-averaged ankle eversion and the ankle frontal-plane movement patterns were similar between the subject groups.

The differences between the subject groups were also examined in landing activities. A recent study by Zhang et al. (75) reported that there were no differences in the inversion, eversion ROMs, two peak vertical GRFs, and peak medial GRF between functional instability and healthy subjects during drop landing from a height of 60 cm. Increased peak eversion velocity was found in functional instability subjects compared to healthy controls. The study showed that the peak lateral and anterior GRFs of the functional instability individuals occurred 10-13 ms earlier on average than control group, suggesting that loading rate of the functional instability subjects was greater than healthy controls. The subjects could not alter their movement patterns to adjust changes of ground in such a short period of time, which therefore may lead to the sprain (11). A sudden ankle inversion produced by trapdoor was used to test peroneal reaction time and postural sway was tested through single-limb standing on the force platform. Increased postural sway and peroneal reaction time were found in functional ankle instability subjects compared to healthy controls (47).

All the subjects in the above studies had functional instability. The CAIT was used in the study by Lin et al. (49) and the AJFAT (58) was utilized in the study by Zhang et al. (75), to determine functional instability. Other studies used inclusion criteria to select people with functional instability (11, 14, 16, 49). Functional instability individuals need to have at least one ankle sprain and one episode of giving way within past six months or twelve months. Involved ankles were reported to be weaker, more painful and less functional than healthy ankles (11, 14, 49, 75). No mechanical testing was used in any of these studies in order to distinguish functional instability and mechanical instability.

In summary, a greater ankle inversion, peak ankle plantarflexion, ankle abduction and loading rate were found during a stop jump task (11, 49) by recreational athletes with functional instability compared to healthy controls. It was also reported that there were no differences in the inversion, eversion ROMs, two peak vertical GRFs, and peak medial GRF between functional instability and healthy subjects during drop landing (75) in these two subject groups. To the knowledge of the author, no joint kinetic variables were reported about CAI subjects during landing on inversion surfaces in the literature.

Difference between Ankle Functional Instability and Mechanical Instability

Two studies have investigated the differences of kinematics and kinetics between functional instability and mechanical individuals using dynamic testing protocols (8, 9). Both anterior drawer and talar tilt were used to test the mechanical instability of subjects. Brown and her colleagues (9) reported that during a stop-jump task, mechanical instability subjects exhibited greater hip flexion and hip external rotation during initial ground contact compared to copers, who are defined as people having ankle sprain injury history but showing no CAI symptoms. Functional instability subjects had less hip flexion ROM than mechanical instability group. The results may be explained by the findings of the study by Horak et al. (41) which showed that individuals with the lack of somatosensory of ankle used a hip strategy more often than healthy controls during anterior and posterior postural translation. In 2008, Brown and the colleagues (8) investigated the kinematic and kinetic differences between mechanical ankle instability, functional ankle instability and copers in five tasks, walk, step down, run, drop jump, and stop jump (8). Most differences were observed in the drop jump and stop jump tasks. The mechanical instability group had greater dorsiflexion at touch down and maximum eversion and less ankle displacement in sagittal plane than copers and functional instability subjects in drop jump, which was inconsistent. In addition they also demonstrated that mechanical instability individuals had small ankle range of motion in sagittal plane than copers and larger ankle displacement in frontal plane than functional ankle instability group and copers in stop jump. For postural control, functional instability people without mechanical instability had longer peroneal reaction time after inversion perturbation than those with only mechanical instability (56). However, it was reported that no difference was found between functional instability people and mechanical instability people in time out of balance of dynamic postural control test via a wobble board (59).

In summary, CAI individuals had greater GRF, greater ankle inversion, less ankle eversion than healthy controls. Functional instability subjects performed differently from mechanical instability subjects. The mechanical instability subjects had greater dorsiflexion at touch down and maximum eversion and small range of motion in sagittal plane during stop jump, and greater hip flexion ROM during stop jump compared to functional instability subjects.

Conclusion

In conclusion, ankle ligament sprain is the most common sports injury (27, 40) and many also experience recurrence and residual symptoms leading to chronic ankle instability (70). The chronic ankle instability model developed by Hertel (33) with three sub-groups is widely used in CAI studies. Hiller et al. (35) expanded the model to include a total of seven subgroups. The anterior drawer and talar tilt tests are two most commonly used manual tests for assessment of ankle mechanical instability (42) .

Researchers usually used two testing protocols to simulate the ankle sprain mechanism: inversion drop (12, 24, 26, 73) and drop landing on inverted surface (12, 20, 30, 31, 64). Landing on inverted surface probably is a more appropriate and demanding for investigating lateral ankle sprain related mechanisms (12). Greater ankle inversion , peak ankle plantarflexion, ankle abduction and GRF loading rate were found in recreational athletes with functional instability during a stop jump task and drop landing onto inverted surface compared to healthy controls (11, 49), while another study showed that there were no differences in the inversion, eversion ROMs, two peak vertical GRFs, peak medial GRF, peak plantarflexion moments and eversion moments between functional instability and healthy subjects during drop landing on flat surface (71). The mechanical instability subjects had greater dorsiflexion at touch down and maximum eversion and small range of motion in sagittal plane during stop jump, and greater hip flexion ROM during stop jump compared to functional instability subjects (8, 9). However, no joint kinetic variables were reported about CAI subjects during landing on inversion surfaces in the literature.

Chapter III
METHODOLOGY

Therefore, the purpose of this study was to investigate kinematic and kinetic differences between CAI individuals with both functional and mechanical instability and healthy subjects in single-leg drop landing on a flat surface, an inverted surface and a combined surface of inversion and plantarflexion. This chapter describes the procedures used in this study and included the following sections: participants, instrumentation, experimental procedures, and data and statistical analysis.

Participants

Participants were divided into chronic instability and healthy groups. A total of 17 male recreational athletes participated in the study. Ten healthy subjects (age: 24.67±2.42 years, mass: 77.23±14.17kg, and height: 1.82±0.09 m) and six subjects with CAI (age: 24±2.10 years, mass: 81.61±9.07 kg and height: 1.83±0.13 m). Since the female subjects had a decreased hip flexion ROM and knee flexion ROM during landing and an increased platarflexion at impact compared to the male subjects, the participants in this study were all male (65). All participants were informed of the purpose and procedures of the study and signed an informed consent form prior to testing. The informed consent form was approved by the Institutional Review Board at the University of Tennessee, Knoxville.

A priori power analysis using GPower (3.1.3, National Instruments Corporation.) was performed to determine necessary sample size. A sample size of 20 provided power of 0.8 with effect sizes of 0.6.

Inclusion Criteria

Healthy Subjects

All participants were recreational active and have a minimum of 1.5 hours per week of physical activity including soccer, volleyball, basketball and football or other sports related to jumping, landing and cutting (8). The participants were free from any major lower extremity injury, able to perform basic physical activities, and free from lateral ankle sprains within 6 months and a history of multiple ankle sprains prior to the testing. All participants were asked to fill out the Cumberland Ankle Instability questionnaire (CAIT, Appendix A) Physical Activity Readiness (PAR-Q, Appendix A), and participant injury history survey form (Appendix A). The control individuals had no history of lateral ankle sprain nor did they exhibit any excessive ligamentous laxity with a score of 1 on a 4-point scale (0=hypomibile, 1=normal, 2= moderate laxity, 3= severe laxity) (37, 38) in the anterior draw test and talar tilt test, and scored ≥ 28 on the CAIT (36). Qualified participants were required to attend to data collection session. The subjects' dominant leg was tested.

Chronic Ankle Instability Subjects

The participants were included in the chronic ankle instability group if they had both functional instability and mechanical instability. Each participant in this group should have had an acute lateral ankle sprain which required non-weight bearing or immobilization for at least three days (8). Each chronic instability individual should have repeated episodes of "giving way" , at least two episodes of giving way or ankle sprain after primary ankle sprain in the past 12 months (7) and had a score ≤ 24 on the CAIT (36). Manual testing was used to determine mechanical instability including anterior drawer and talar tilt tests (8, 9, 59). The ankle was graded as: 0=hypomibile, 1=normal, 2= moderate laxity, 3= severe laxity (Hiller et al., 2007). The subjects with a grade of 2 (moderately hypermobile) or 3 (severe laxity) were included in the

CAI group. For participants with bilateral instability, the more severely affected ankle was analyzed. The ankle with greater manual test scores (greater mechanical instability) was selected to be tested. The ankle with the lower CAIT score was selected to be tested if both ankles had the same score of the manual tests (35). If the subjects have the same CAIT and mechanical testing scores in both ankles, the dominant leg (determined by asking which foot they would kick a ball with) was tested. For mechanical instability, the average scores of both manual tests were used to determine which ankle was considered as being more severely affected.

Exclusion Criteria

Exclusion criteria for both subject groups included a history of major injuries and surgeries (e.g., ACL reconstruction, total/partial knee or hip replacement, bone fractures) in the lower extremity and trunk, and any minor injuries in the lower extremity and trunk (e.g., obvious swelling, discoloration, pain, self-reported knee and /or hip instability) within three months prior to the testing, or being involved in a current rehabilitation program (8).

Instrumentation

Anthropometric Measures

Body mass (kg) and height (m) of participants were measured by a calibrated physician's scale.

Shoe

Participants will wear a pair of neutral lab running shoes (Noveto, adidas) during biomechanical tests.

Inverted and Combined Surfaces

A customized inverted surface platform [39.37cm (W) × 50.80cm (L) × 30.48cm (H)] with a 25˚ of inversion was used in the testing and mounted on the right force platform with double-sided tape for the inverted surface landing condition. Strips of anti-slip stair tread were adhered to the surface to prevent slipping during landing on the surface. The device allows the ankle to be inverted 25˚ after the drop landing from the overhead bar.

A customized combined surface platform [39.37cm (W) × 50.80cm (L) ×30.48cm (H)] with a 25˚ of inversion and 25˚ of plantarflexion was mounted on the right force platform with double-sided tape. Strips of the same anti-slip stair tread were also used on the surface to prevent slipping during landing on the surface. The device allows the ankle to be inverted and plantarflexed after the drop landing from the overhead bar.

Adjustable Overhead Bar

A motorized and adjustable overhead bar mounted from the ceiling was used to place the participant at a height 0.3m above the center of the inverted surface and combined surface from the mid-heel of the interested foot for CAI participants or right foot for healthy participants.

3-Dimensional High-speed Video System

A 9-camera infrared motion capture system (240Hz, Vicon Motion Analysis, Inc., Oxford, UK) was utilized to collect 3-dimensional (3D) kinematic data. Retroreflective markers were placed directly on the lower extremity. Anatomical reflective markers were placed bilaterally on the acromion process, greater trochanter, medial and lateral femoral epicondyles, medial and lateral malleoli, 1st and 5th metatarsal heads, and toe (most anterior aspect of the shoe). Six semi-rigid thermoplastic shells with four tracking markers each were placed on the trunk, pelvis, thighs, and shanks during dynamic trials. In addition, three discrete tracking markers were placed on the posterior and lateral heel counter of each shoe. A static trail was taken first with the anatomical and tracking markers on the participant. The anatomical markers were then removed before dynamic movement trails.

Force Platforms

Two force platforms (1200 Hz, Advanced Mechanical Technology, Inc., Watertown, MA 02472, USA) were used to collect GRF and moments of forces. The 3D kinematic data and GRF data were collected simultaneously using the Vicon system and the Vicon Nexus software (Version 11.0, Vicon Motion Analysis, Inc., Oxford, UK).

Experimental Procedures

The study included two testing sessions, a screening session and a dynamic testing session, which were conducted in the Biomechanics/Sport Medicine Lab at the University of Tennessee, Knoxville. The subjects were asked to fill out questionnaires about his/her injury history, physical activity, and subject demographic information. They are also required to fill out the CAIT and PAR-Q.

Manual Testing

Ankle laxity for all subjects was tested and rated by a certified athletic trainer with over 3 years of clinical experience. A talar tilt was performed with the subject placed in a supine on a treatment table and the ankle in plantarflexion (59). The calcaneum is cupped by one hand (right foot/left hand and vice versa) while the other hand wraps over the dorsum of the foot, the fingers positioned over the lateral talar dome and the thumb supporting the sole of the foot. The examiner’s thumb was used to detect the gapping between the lateral malleolus and the talus (54). The excursion of the talus was graded as: 0=hypomobile, 1=normal, 2= moderate laxity, 3= severe laxity (37, 38) . The anterior drawer test was performed with the subject in a supine on the treatment table with the knee flexed at 60 degrees and supported at the foot/ankle to help eliminate the tension of the gastrocnemius muscle (59). The amount of anterior movement in the talocrural joint was determined by palpating the movement occurred between the talus and the malleoli, using the thumb and index finger on the lateral and medial aspects, respectively. This movement was graded using the same scale stated above for the talar tilt test (37, 38).

Drop Landing

During the second part of the dynamic testing session, the subjects performed five trials in each of four drop landing movement conditions from 0.3 m: 1) a drop landing on to the force platforms with both legs, 2) a drop landing on to the force platform with the affected (CAI) or dominant leg, 3) a drop landing on to the inverted surface with the affected (CAI) or dominant leg, 4) a drop landing on to the combined surface with the affected (CAI) or dominant leg. The single-leg and two-leg drop landings were first randomized. The drop landings on the inverted and combined were randomized afterwards.

The participants were enough time to practice and become familiar with drop landing conditions. The participants were asked to look in front during landing instead of looking down. For double-leg drop landing, participants were asked to land in a self-selected normal landing technique so that the right foot and left foot landed on the right and left force platforms, respectively. For the single-leg landings, subjects were asked to land on the surface with the test leg on to the force platform. For the single-leg landing the inverted or combined surfaces, the testing foot should land on the middle of the inverted or combined surface. The trial would not be considered as successful if subjects lost balance, touched the floor or hopped with non-testing limb during landing phase.

Data and Statistical Analysis

GRF was filtered at the frequency of 100Hz with a low-pass filter for GRF values. 3D marker trajectories and GRF data then filtered at 15 Hz – for inverse dynamics The GRF, kinematic and joint kinetic data of the drop landing trials were analyzed during the landing phase which was defined as the time between the foot contact and the maximum knee flexion after the contact.

Visual3D software suite (C-Motion, Inc.) was used to compute three-dimensional (3D) kinematic variables of the lower extremity joints. An X-Y-Z Cardan sequence was used in the 3D kinematics computation and a right-handed rule was used to determine positive and negative signs for angular kinematic and kinetic variables. A customized computer program (VB_V3D) was used to generate scripts and models to be used in Visual 3D and determine critical values of variables of interest. Another customized program (VB_Table) was used to generate statistical files and organize data tables. GRFs were normalized to body weight (BW) and joint moments were normalized to body mass (Nm/kg).

The dependent variables include peak vertical and lateral GRFs, loading rate of lateral and vertical GRF, contact ankle front-plane angle, maximum inversion and eversion angles, inversion and eversion ROM, contact plantarflexion angle, maximum dorsiflexion angle and ROM, peak eversion and plantarflexion moments. For the knee, maximum knee flexion angle and moment, maximum abduction angle and adduction moments were also analyzed.

In order to examine the differences between CAI and healthy groups, and the landing tasks, the dependent variables were analyzed using one 2 × 4 (group × landing condition) mixed design analysis of variance (ANOVA) with an alpha level of 0.05 (SPSS 20.0, SPSS Inc., Chicago, IL). Post hoc comparisons were performed using a paired-sample t-test.

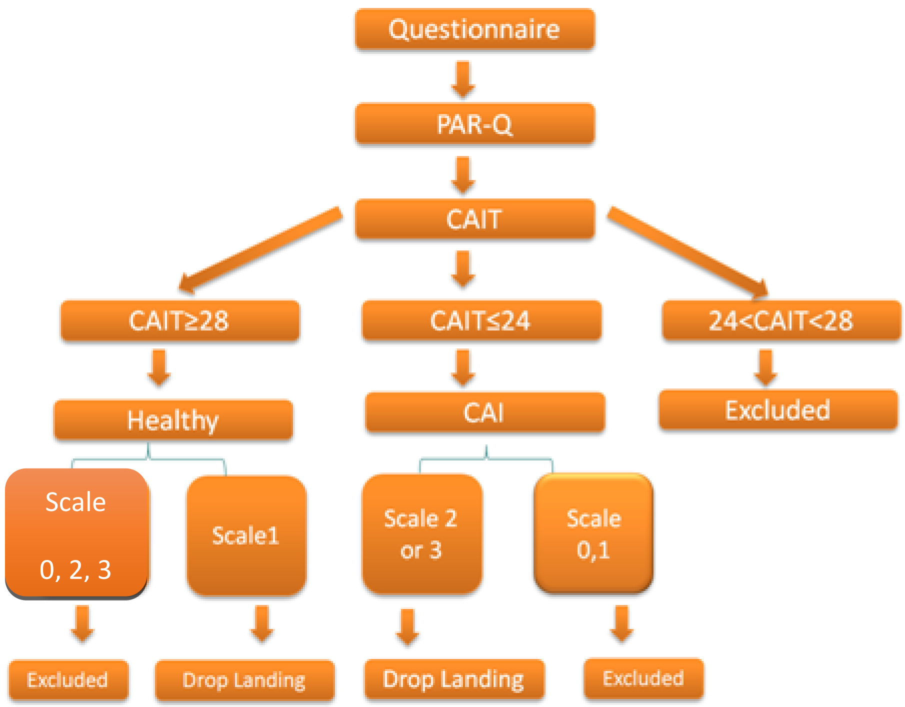


Figure 3. Experimental Procedures

Chapter IV
BIOMECHANICAL DIFFERENCE BETWEEN CHRONIC ANKLE INSTABILITY INDIVIDUALS AND HEALTHY INDIVIDUALS AND HEALTHY INDIVIDUALS DURING LANDING ON FLAT ON FLAT, INVERTED AND COMBINED SURFACES

Abstract

Lateral ankle sprains most frequently occurs during sports. Individuals who experienced a first time ankle sprain had a high reoccurrence rate and residual symptoms and functional instability leading to chronic ankle instability (CAI). The primary purpose of this study were to investigate kinematic and kinetic differences between CAI individuals and healthy subjects in single-leg drop landing on a flat surface, an inverted surface and a combined surface of inversion and plantarflexion. A total of 17 subjects (6 subjects with chronic ankle instability, 11 healthy subjects) performed five trails in each of four dynamic movement conditions of drop landing from a height of 30 cm onto a force plat form: double leg landing, single-leg drop landing on flat surface, inversion surface of 25 degrees and combined surfaces of 25 degrees of inversion and 25 degrees of plantarflexion. A nine-camera motion analysis system was used to capture the movement of dynamic testing. A 2 × 4 (ankle stability × surfaces) repeated measures ANOVA was used to evaluate the variables for dynamic testing ($p<0.05$). The results showed that single-leg landing on inverted surface resulted in significantly greater peak inversion, peak inversion ROM and peak eversion moment. Greater peak lateral GRF, shorter time to peak lateral GRF, and peak vertical GRF and its loading rate coupled in single-leg landing on combined surface were found compared to landing on inverted surface. These results may suggest single-leg

landing on combined surface may be even more challenging and more suitable than inverted surface as a testing protocol in investigating lateral ankle sprain related issues.

Introduction

Lateral ankle sprains most frequently occurs during sports (27, 40). Excessive inversion when ankle is in plantarflexion is the most common lateral ankle sprain mechanism (28). It has also been demonstrated that individuals who experienced a first time ankle sprain had a 73.5% reoccurrence rate and 59% of them had residual symptoms and functional instability, which are the major factors leading to chronic ankle instability (CAI) (33).

A CAI widely accepted model developed by Hertel (33) suggested that when both functional instability (FI) and mechanical instability (MI) are present, recurrent ankle sprain occurs. Functional instability may result from a lack of proprioception, neuromuscular-recruitment, postural control and strength. Mechanical instability may result from changed anatomic mechanics after the first and/or subsequent ankle sprains (33). Hiller et al. (35) proposed a new and expanded CAI model developed from Hertel's original model (33) and was able to demonstrate with their CAI data that mechanical instability and recurrent sprain can exist either independently or co-exist. Therefore, both functional instability and mechanical instability should be considered into investigation of CAI.

Several surveys have been used in the literature to evaluate FI. It was demonstrated that the CAIT is a simple, valid and reliable measurement for FI and have acceptable construct validity and internal reliability (36). In a review study, it was demonstrated that the relationship between MI and FI had not been established in the literature and MI subjects tended to be excluded when investigation of FI (13). Functional instability assessments correlate with mechanical instability measures poorly (43, 67). In the study by Habbard et al. (43), it was shown that both ankle MI and FI measurements were not totally dichotomous and should be done together. Anterior drawer and talar tilt tests are two of the most commonly used manual tests for assessment of ankle MI and can be utilized to examine the integrity of ligaments (42). A 4-point scale of 0 to 3 (0=hypomobile, 1=normal, 2= moderate laxity, 3= severe laxity) in order to quantify ankle mechanical instability has been used (37, 38).

Drop landing on inverted surface, inversion drop (from a trapdoor) and step-off landing have been used to simulate ankle inversion mechanism. Greater maximum inversion velocity was found in drop landing compared to inversion drop (12). Landing on inverted surface from higher height simulates the actual ankle sprains during landing on uneven surface and therefore is a more appropriate and demanding for investigating lateral ankle sprain related mechanisms (12). In a study of single-leg drop landing on to a 20˚ inversion surface, increased ankle eversion moment was observed in the braced condition compared to no brace condition (64). Hagins et al. (31) found that in landing off a 40 cm platform onto slope with 3.6˚, 11.2 % body weight (BW) higher GRF in lateral direction was found compared to landing on a flat surface. Gutierrez et al. (30) showed significantly increased peak ankle plantarflexion, adduction and inversion during inversion step-off landing compared to landing on an even surface from 30 cm. Very few studies of drop landing on the combined surface were found in the literature (4). In a study of double-leg drop landing from 30 cm onto a flat surface, an inversion surface of 25˚ and a combined surface of 25˚ inversion and 25˚ plantarflexion, greater peak ankle inversion angle and peak inversion velocity were found for landing on the inverted compared to the flat and combined surfaces and increased peak dorsiflexion angle was observed during inverted surface landing compared to combined surface landing (4).

There were some differences between CAI and healthy subjects during bilateral double-leg landing. A greater loading rate of anterior and lateral ground reaction force (GRF) was found in recreational athletes with functional instability during stop jump and drop landing onto inverted surface compared to healthy controls (11). However, it was shown that there were no differences in the inversion, eversion Range of Motions (ROMs), peak vertical GRFs, and peak medial GRF between functional instability and healthy subjects during drop landing on flat surface (75). In the study by Gutierrez and et al. (30) , all subjects were asked to perform double-leg landing from a platform from 30 cm with the test limb on a 25˚ inverted surface. No differences were found in ankle laxity measurements using an instrumented arthrometer, indicating lack of differences in mechanical instability. No significant differences among CAI, copers and healthy subjects were found for inversion and plantarflexion angle at touchdown, maximum ankle plantar flexion, adduction, and inversion angles after touchdown. The authors attributed this lack of differences to large variability in the data and suggested that both hypomobile and hypermobile subjects were included in all three subject groups. It has been demonstrated that FI subjects performed differently from mechanical instability subjects. Another previous study showed the the peak lateral and anterior GRFs of the functional instability individuals occurred 10-13 ms earlier on average than control group, suggesting that loading rate of the functional instability subjects was greater than healthy controls. The subjects could not alter their movement patterns to adjust changes of ground in such a short period of time, which therefore may lead to the sprain (11).The MI group had greater dorsiflexion at touch-down and maximum eversion and small range of motion in sagittal plane during stop jump, and greater hip flexion ROM during stop jump compared to functional instability subjects (8, 9).

Moreover, no joint kinetic variables have been reported about CAI subjects during landing on inversion or combined surfaces in the literature.

Most studies only focused on kinematics and adopted flat drop landing and inversion drop landing. Few studies adopted combined drop landing. In addition, the previous studies did not usually differentiate mechanical and functional instability in their subjects. Therefore, the purpose of this study was to investigate kinematic and kinetic differences between CAI individuals with both functional and mechanical instability and healthy subjects in single-leg drop landing on a flat surface, an inverted surface and a combined surface of inversion and plantarflexion. The main hypothesis was that CAI individuals would have greater peak lateral GRFs, loading rate of vertical and lateral GRF, ankle contact front-plane angle, maximum inversion, inversion ROM, contact plantarflexion angle, and peak eversion. The secondary hypothesis of the current study are that peak mediolateral GRF, peak inversion, peak inversion ROM, peak eversion moment would be greater in landing on inverted surface compared to flat surface; and there would be greater peak inversion and dorsiflexion in landing on inverted surface compared to combined surface.

Materials and Methods

Subjects: A total of 17 male recreational athletes participated in the study. Ten healthy subjects (age: 24.67±2.42 years, mass: 77.23±14.17kg, and height: 1.82±0.09 m) and six subjects with CAI (age: 24±2.10 years, mass: 81.61±9.07 kg and height: 1.83±0.13 m). All of the subjects were free from any major lower extremity injury, able to perform basic physical activities, and free from lateral ankle sprains within 6 months. The healthy subjects had no history of lateral ankle sprain nor did they exhibit any excessive ligamentous laxity with a score of 1 on a 4-point scale (0=hypomibile, 1=normal, 2= moderate laxity, 3= severe laxity) (37, 38) in the anterior draw test and talar tilt test, and scored ≥ 28 on the CAIT (36). To qualify for the CAI group, subjects should have a history of multiple ankle sprains prior to the testing and have repeated episodes of "giving way" , at least two episodes of giving way or ankle sprain after primary ankle sprain in the past 12 months (7). They also had a score ≤ 24 on the CAIT (36), and a grade of 2 (moderately hypermobile) or 3 (severe laxity) in both anterior drawer and talar tilt tests.

Instrumentation: A 9-camera infrared motion capture system (240Hz, Vicon Motion Analysis, Inc., Oxford, UK) was utilized to collect three-dimensional (3D) kinematic data. Retroreflective markers were placed directly on the lower extremity. Two force platforms (1200 Hz, Advanced Mechanical Technology, Inc., Watertown, MA 02472, USA) were used to collect GRF and moments of forces. The 3D kinematic data and GRF data were collected simultaneously using the Vicon system and the Vicon Nexus software (Version 11.0, Vicon Motion Analysis, Inc., Oxford, UK). A customized inverted surface platform [39.37cm (W) × 50.80cm (L) × 30.48cm (H)] with a 25˚ of inversion (Figure 1a) and a combined (Figure 1b) surface platform [39.37cm (W) × 50.80cm (L) ×30.48cm (H)] with a 25˚ of inversion and 25˚ of plantarflexion were used in the testing and mounted on one force platform with double-sided tape. Strips of anti-slip stair tread tape were adhered to the surface of the two landing surfaces to prevent slipping during landing. A motorized and adjustable overhead bar mounted from the ceiling was used during drop landing trials to place the participant at a height 0.3m above the center of the inverted surface or combined surface from the mid-heel of the testing foot.

Experimental Protocols: The study included two testing sessions, a screening session and a biomechanical testing session. The subjects were asked to fill out questionnaires about his/her injury history, physical activity, and subject demographic information. They are also required to fill out the CAIT and Physical Activity Readiness Questionnaire. In addition, the talar tilt and anterior drawer tests were performed on all subjects rated by two certified athletic trainer (one with over 3 years of clinical experience and the other with 1 year and a half of clinical experience). The two manual tests were graded as 0 - hypomobile, 1 - normal, 2   moderate laxity, and 3 - severe laxity (37, 38). During the biomechanical testing session, the subjects performed five trials in each of four drop landing movement conditions from 0.3 m: 1) a drop landing on to the force platforms with both legs, 2) a drop landing on to the force platform with the affected (CAI) or dominant leg (control), 3) a drop landing on to the inverted surface with the affected (CAI) or dominant leg, and 4) a drop landing on to the combined surface with the affected (CAI) or dominant leg. The subjects were given enough time to practice to become familiar with drop landing conditions. The subjects were asked to look in front during landing instead of looking down during actual testing. For double-leg drop landing, participants were asked to land in a self-selected normal landing technique so that the right foot and left foot landed on the right and left force platforms, respectively. For the single-leg landings, subjects were asked to land on the surface with the test leg on to the force platform. For the single-leg landing the inverted or combined surfaces, the testing foot should land on the middle of the inverted or combined surface. A trial was considered to be considered as successful if subjects did lose balance, touch the floor with non-testing limb during landing phase or hop.

Data and Statistical Analyses. To obtain peak GRF values, GRF signals were filtered at a cutoff frequency of 100Hz with a low-pass Butterworth digital filter. For joint kinematic and kinetic calculations, 3D marker trajectories and GRF data were filtered at a cutoff frequency of 15 Hz using a low-pass Butterworth digital filter (48). The GRF, kinematic and joint kinetic data were analyzed during the landing phase which was defined as the time between the foot contact and the maximum knee flexion after the contact.

Visual3D software suite (C-Motion, Inc.) was used to compute 3D kinematic and kinetic variables of the lower extremity joints. An X-Y-Z Cardan sequence was used in the 3D kinematics computation and a right-handed rule was used to determine positive and negative signs for angular kinematic and kinetic variables. Customized computer programs (VB_V3D and VB_Table) were used to generate scripts and models to be used in Visual 3D, determine critical values of variables of interest and organize data for statistical analyses. GRFs were normalized to body weight (BW) and joint moments were normalized to body mass (Nm/kg).Dependent variables included peak mediolateral GRF, time to peak mediolateral GRF, peak vertical GRF, loading rate of peak vertical GRF, contact plantarflexion, dorsiflexion ROM, peak eversion/inversion, peak eversion/inversion ROM, peak plantarflexion moment, knee flexion ROM, knee adduction ROM, peak extension moment and peak abduction.

In order to examine the differences between CAI and healthy groups, and the landing tasks, the dependent variables were analyzed using a 2×4 (group × landing condition) mixed design analysis of variance (ANOVA) with an alpha level of 0.05 (SPSS 20.0, IBM SPSS Inc., Chicago, IL). Since the main interest of the study was differences between the three surface conditions during single-leg landing, when a significant group by condition interaction occurred a 2×3 (group × condition) was performed to further examine the interaction among the three single-leg landing conditions. If the interaction was no longer significant, no post hoc comparisons were performed. Otherwise, post hoc comparisons were performed using a paired-sample t-test.

Results

The independent samples t-test showed that there were no differences in age, height, weight, BMI (Body Mass Index) between healthy and CAI subjects. Significant difference were found between two subject groups in talar tilt (healthy: 1.00±0.00 & CAI: 2.00±0.00, $p<0.001$), and anterior drawer (healthy: 1.00±0.00 & CAI: 1.72±0.57, $p=0.011$) and CAIT (healthy: 28.92±1.00 & CAI: 23.5±0.84, $p=0.023$).

<u>Ground Reaction Force</u>

Representative GRF curves are presented in Figure 2. The peak lateral GRF was greater in single-leg landing on combined surface compared to flat ($p=0.001$) and inverted ($p=0.002$) surfaces (Table 1). The time to the peak lateral GRF was shorter in single-leg landing on inverted ($p=0.04$) and combined ($p<0.001$) surfaces compared to flat surface, and was also shorter in the combined surface compared to the inverted surface ($p<0.001$). The peak vertical GRF in landing on inverted was smaller than flat ($p<0.001$) and combined surface ($p=0.005$). Loading rate of vertical GRF was greater in landing on combined surface compared to flat ($p<0.001$) and inverted surface ($p<0.001$), and was greater on inverted surface compared to flat surface ($p=0.026$). The peak medial GRF in double-leg landing on flat surface was different from the peak lateral GRF in single-leg landing on flat surface ($p<0.001$, Table 1). Peak vertical GRF ($p<0.001$) and its loading rate ($p<0.001$) in double-leg landing on flat surface were smaller than flat surface.

<u>Ankle Kinematics and Kinetics</u>

Representative ankle kinematic and kinetic curves are presented in Figures 3 and 4, respectively. Greater plantarflexion contact angle was found in landing on flat surface compared to inverted surface ($p=0.023$, Table 2). The dorsiflexion range of motion (ROM) of single-leg landing on flat surface was greater than inverted surface ($p=0.001$) and combined surface ($p<0.001$), and the dorsiflexion ROM of landing on inverted surface was greater on combined surface ($p<0.001$, Table 2). The peak inversion in landing on inverted surface was higher than combined surface ($p<0.001$). The inversion ROMs in landing on inverted surface was greater than combined ($p<0.001$),and flat surface ($p<0.001$). The peak plantarflexion moment was greater in landing on flat surface and inverted surface ($p<0.001$) compared to combined surface ($p<0.001$, Table 2). Smaller peak eversion moment was found in landing on flat surface compared to inverted ($p<0.001$) and combined ($p<0.001$) surfaces. There were group×condition interaction for contact plantarflexion angle ($p=0.003$) and dorsiflexion ROM ($p=0.023$). After removing double-leg landing and re-analyzing data with data only from single-leg landing on flat, inverted and combined surfaces, the group × condition interactions for contact plantarflexion angle and dorsiflexion ROM were no longer significant. Therefore, the post hoc comparisons were ignored as the original significant interactions were due to double-leg landing which was not a major interest.

The contact plantarflexion angle was smaller in double-leg landing on flat surface than single-leg landing on flat surface ($p=0.017$, Table 2). Greater dorsiflexion ROM was found in double-leg landing compared to single-leg landing on flat surface ($p=0.021$). Peak eversion in double-leg landing on flat surface was smaller than single-leg landing on flat surface ($p<0.001$). Greater peak plantar flexion moment was found in single-leg landing on flat surface than double-leg landing on flat surface ($p<0.001$).

Knee Kinematics and Kinetics

Representative knee kinematics and kinetics are presented in Figure 4.The knee flexion ROM in landing on combined surface was smaller than that of landing on inverted surface (p=0.015, Table 3). The knee adduction ROM for healthy subjects was smaller compared to CAI subjects (p=0.003).The knee adduction ROM in landing on flat surface was smaller compared to inverted (p<0.001) and combined (p<0.001) surfaces. The knee extension moment in landing on combined surface was greater than flat (p=0.03) and inverted (p<0.001) surfaces. The knee abduction moment in landing on flat surface was smaller than inverted (p<0.001) and combined surface (p<0.001).Knee flexion ROM was greater in double-leg landing on flat surface than single-leg landing on flat surface (p<0.001, Table 3). Peak extension moment (p<0.001) and peak abduction moment (p<0.001) in double leg landing on flat surface was smaller than single-leg landing on flat surface (p<0.001).

Discussion

The purpose of the study was to investigate kinematic and kinetic differences between CAI subjects with both functional and mechanical instability and healthy subjects in single-leg drop landing on a flat surface, an inverted surface and a combined surface of inversion and plantarflexion. The main hypothesis was that CAI subjects would have greater peak vertical and lateral GRFs, loading rate of lateral GRF, maximum inversion, inversion ROM, contact plantarflexion angle, peak eversion. The results from the current study showed that there was no significant difference for the kinetics and kinematics for the hypothesized variables between CAI subject and healthy subjects, except for knee abduction ROM, indicating the primary hypothesis was not supported. A recent study of single-leg land-cut task using CAI and healthy subjects showed no significant differences of inversion/eversion, dorsiflexion/plantarflexion, toe-in and toe-out between groups (46). The authors suggested the lack of group differences was due to the lack of mechanical instability test to determine the ankle laxity. Tegner score (a self-assessment of knee function at specific activity level) was used to determine the activity level of subjects to make sure both group were at the same level. Although both functional and mechanical instability tests were used on both CAI and healthy subjects in the current study, no significant differences were find between CAI and healthy subjects except for knee adduction ROM. CAI subjects had greater knee adduction ROM than that of healthy subjects. The CAI subjects may try to obtain same ankle motion as healthy subjects in order to prevent from recurrent injury with compensations of greater knee motion. The lack of group difference may be related to the high variability in performing the landing tasks and some subjects used a stiffer landing style than others in the inverted and combined surfaces. The small sample size of the CAI group may also limit possibility of finding group differences.

The secondary hypothesis of the current study are that peak mediolateral GRF, peak inversion, peak inversion ROM, peak eversion moment would be greater in landing on inverted surface compared to flat surface. The discussion was mainly about the differences between conditions since there was only one group difference. The ankle everted and had eversion ROM in single-leg landing on flat surface while it inverted and had inversion ROM on inverted and combined surfaces due to the 25° of inversion angle for both inverted and combined surfaces. Our data also showed that the peak eversion moments in single-leg landing on inverted were much greater than that on flat surface, indicating that ankle evertors exerted greater torque against greater ankle inversion loading during landing in these inclined surfaces for protection against ankle inversion loading. Greater peak inversion velocity (12, 20) and shorter time to peak inversion (12, 72) were reported in landing on inverted surface compared to flat surface, suggesting landing on inverted surface was more challenging. The greater ankle eversion moment found in inverted surfaces may be also related to the slightly increased but non-significant peak lateral GRF compared to landing on flat surface. In addition, the time to peak mediolateral GRF was decreased in the single-leg landing on inverted surfaces. Along with the increased peak mediolateral GRF, these results suggest greater loading rate of peak frontal-plane GRF. Previous studies have also showed greater peak mediolateral GRF (31) and peak inversion (12, 20, 30, 72) in landing on inverted surface compared to flat surface. Those results from the literature provide support to the greater ankle inversion loading in single-leg landing on the inverted surfaces in the current study. Furthermore, the current study also showed that greater knee adduction ROM and abduction moment of landing on inverted and combined surfaces was shown compared to flat surface. These knee results indicated that greater frontal-plane ankle motion also increased the frontal plane knee motion and loading.

The current study showed that peak vertical GRF and its loading rate in landing on flat surface were greater compared to inverted surface, which is consistent with findings from a previous study (72, 75). It was suggested that anti-slip surface (sand paper) used to prevent slip for landing on the inverted surface required greater friction which may cause a greater energy dissipation therefore reduced the peak vertical GRF (72). An anti-slip stair tread tape was used on both inverted and combined surface to prevent slip in the current study. It was suggested that smaller dorsiflexion ROM in landing on inverted surface compared to the flat surface indicated a stiffer landing strategy adopted by the subjects in landing on inverted surface compared to the flat surface (72, 75). The ankle joint was constrained by the 25° inversion of surface leading to decreased ROM and therefore the reduced peak vertical GRF. This stiffer strategy and the reduced eversion motion with landing on the inverted surface place the ankle and the rest of the lower extremity in an unfavorable position for impact attenuation, which also included greater knee adduction ROM and abduction moment. The previous study reported decreased peak mediolateral GRF in landing on inverted surface compared to flat surface (72, 75), while the current study showed greater peak mediolateral GRF in landing on inverted surface. The difference may be due to the different types of landing used in these two studies. In the double-leg landing used in the study by Zhang et al.(75), subjects might place the contact foot more laterally underneath of COG which may be related to reduced peak lateral GRF. In the single-leg landing used in this study, however, the landing leg was the only support for the whole body and subjects had to land more medially in order to maintain balance.

We also hypothesized that there would be greater peak inversion and dorsiflexion in landing on inverted surface compared to combined surface. It was suggested that landing on combined surface provides a more suitable surface condition simulating lateral ankle sprains (4). However, the study used a double-leg leg landing on flat, inverted and combined surface (4). The current study investigated single-leg landing on three similar surfaces. We found no difference in contact plantarflexion angle in single-leg landing on inverted and combined surfaces, but greater dorsiflexion ROM in landing on inverted surface, indicating greater peak dorsiflexion in landing on inverted surface compared to combined surface. Therefore this part of the hypothesis was supported. In addition, it was not surprising that the 25° plantarflexion and inversion combined surface induced a much smaller dorsiflexion ROM in single-leg landing compared to inverted surface as subjects made foot contact to a plantanarflexed surface and the foot and ankle were kept in the plantarflexed position and therefore ankle was less dorsiflexed. The smaller peak plantarflexion moment on combined surface compared to inverted surface supported the result of smaller dorsiflexion ROM as it indicated that the plantarflexors did not have to work as hard on the combined surface during the landing task.

On the other hand, the peak inversion and peak inversion ROM were smaller in landing on combined surface compared to inverted surface, which is consistent with the findings from the previous study (72) and supported our hypothesis. However, peak eversion moment was not reduced in landing on the combined surface compared to inverted surface, indicating that the loading of peak lateral GRF was similar in both inclined surfaces. The smaller inversion ROMs and unchanged peak eversion moment for landing on combined surface indicated the ankle may experience similar or even greater level of inversion loading. The claim of greater inversion loading is supported by the greater peak lateral GRF, shorter time to peak lateral GRF, and peak vertical GRF and its loading rate. In addition, smaller knee flexion ROM was found for combined surface compared to inverted surface. Therefore, these results suggest that the subjects adopted a stiffer landing style in single-leg landing on combined surface. This is the first study which investigated both ankle and knee kinematic and kinetic differences in landing on flat, inverted and combined surfaces. It provided further evidences for the combined surface as a choice of testing protocol it is a more suitable landing surface for studying lateral ankle sprains and related mechanisms than regular flat and even the inverted surface.

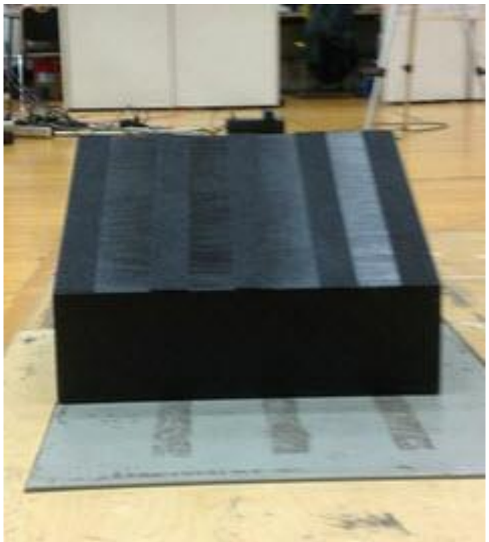
The peak vertical GRFs of the current study for both groups (Healthy: 2.7 BW and CAI: 2.6 BW) are similar to the results in an anticipated single-leg landing (2.6 BW) of a previous study (20) investigating the difference between anticipated and unanticipated single-leg drop landing. The study showed that subjects had greater peak vertical GRF in unanticipated single-leg drop landing. In realistic sporting events, inversion ankle sprains mostly occurred in a sudden landing without preparation. Unanticipated single-leg drop landing may be more close to the actual performance during sports. The authors reported greater peak vertical GRF, peak inversion, inversion velocity were greater in unanticipated landing on unanticipated single-leg landing on inverted surface compared to unanticipated single-leg landing on inverted surface. Combined surface which combined ankle inversion and plantarflexion may simulate lateral ankle sprain better as previously discussed and therefore unanticipated single-leg landing on combined surface might be an even more close to actual situation for lateral ankle sprains. This study only focused on the ankle and knee joints. What roles the hip and trunk would play during the single-leg landing on flat, inverted and combined surfaces warrant further studies.

There were clear differences between single-leg and double-leg landing on flat surface. There was peak medial GRF in double-leg landing and peak lateral GRF in single-leg landing. Peak vertical GRF and its loading rate were greater in single-leg landing which may explain smaller knee flexion ROM and greater knee extension moment. Greater peak eversion and eversion ROM were also found in single-leg landing on flat surface suggesting that more frontal-plane ankle motion due to greater mechanical demands associated with single-leg landing. which are consistent with the previous findings (65).

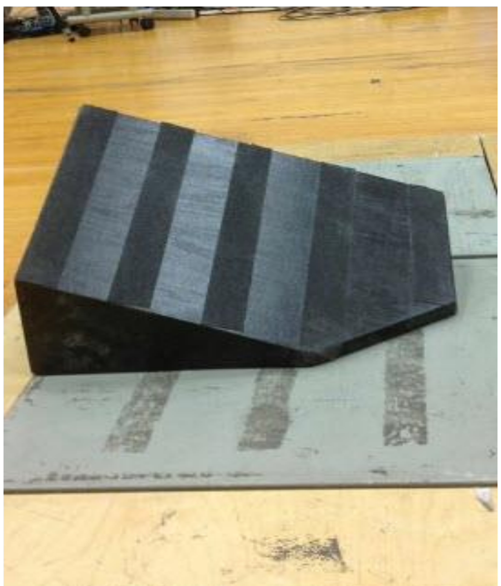
There were several limitations for the study. The lack of significant group differences between CAI subjects and healthy subjects may be related to the high variability in performing the landing tasks and some subjects used stiffer landing than others. A limitation for this study was that the peak knee flexion angle during landing was not monitored. The rating of current level of physical activity might be more precise using different instruments such as Tegner scale and Godin Leisure-Time Exercise Questionnaire instead of minimum number of hours per week of participation in physical activity (29). Some subjects may play sports six or seven hours per week, and others may just work out two hours per week, which could make differences in the biomechanical responses in drop landing. With only six subjects in the CAI group, small sample size certainly might have limited possibility of finding significant group differences. Additionally, the study only investigated male recreational athletes and how female would perform in such protocol is unknown. Since the females tend to have stiff landing than males, there might be some differences in lower extremity.

Conclusion

This is the first study that investigated the ankle and knee kinematic and kinetic differences in landing on flat, inverted and combined surfaces. The results showed that single-leg landing on inverted surface resulted in significantly greater peak inversion, peak inversion ROM, peak eversion moment as hypothesized, suggesting greater ankle inversion loading during landing in inverted surfaces for protection against ankle inversion loading. The inverted surfaces were more challenging than the flat surface. The greater peak lateral GRF, shorter time to peak lateral GRF, and peak vertical GRF and its loading rate coupled with the unchanged peak eversion moment in single-leg landing on combined surface compared to landing on inverted surface indicated the ankle may experience similar or even greater level of inversion loading. These results may suggest single-leg landing on combined surface might be even more suitable than single-leg landing inverted surface as a testing protocol in investigating lateral ankle sprain related issue

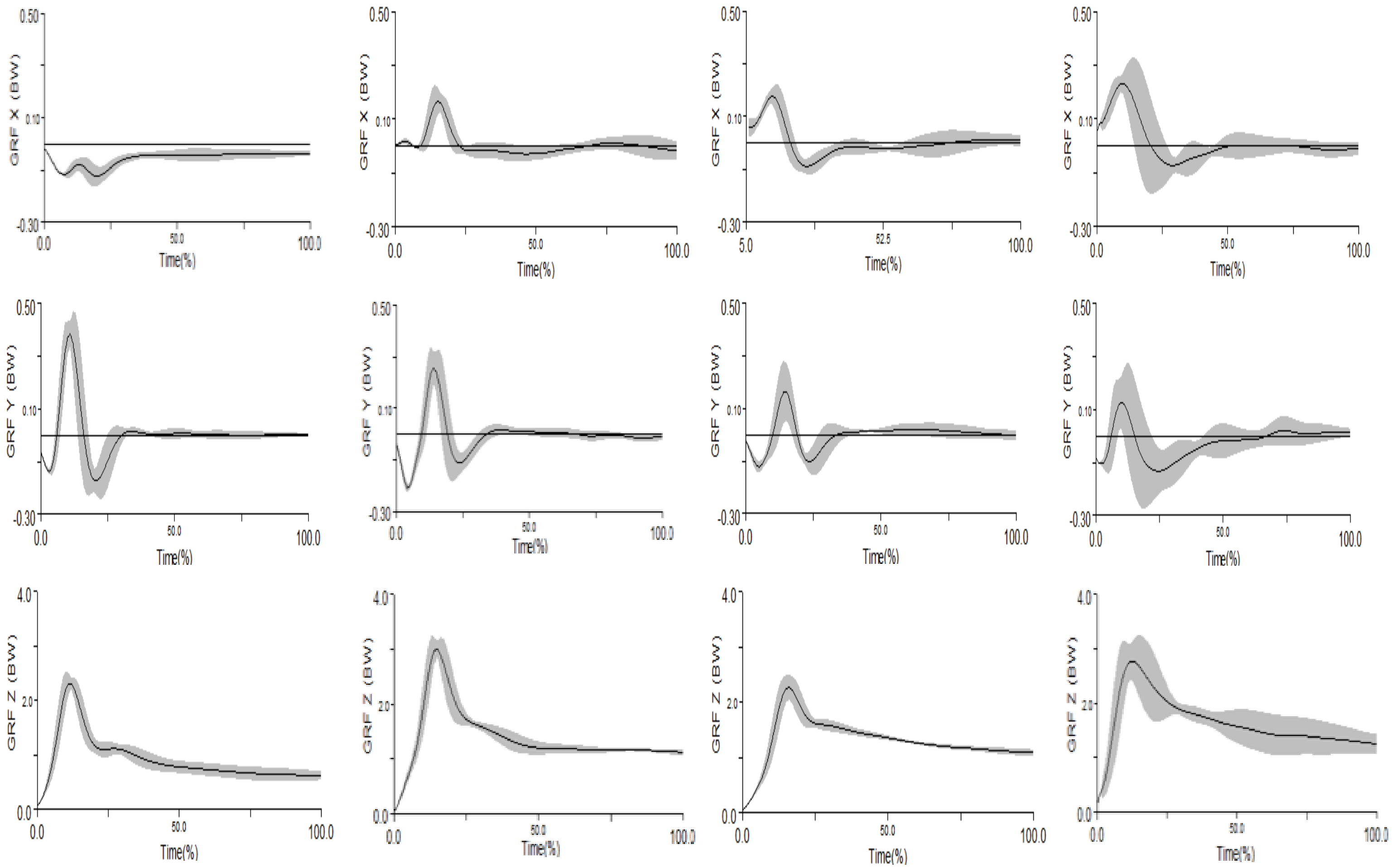


A)



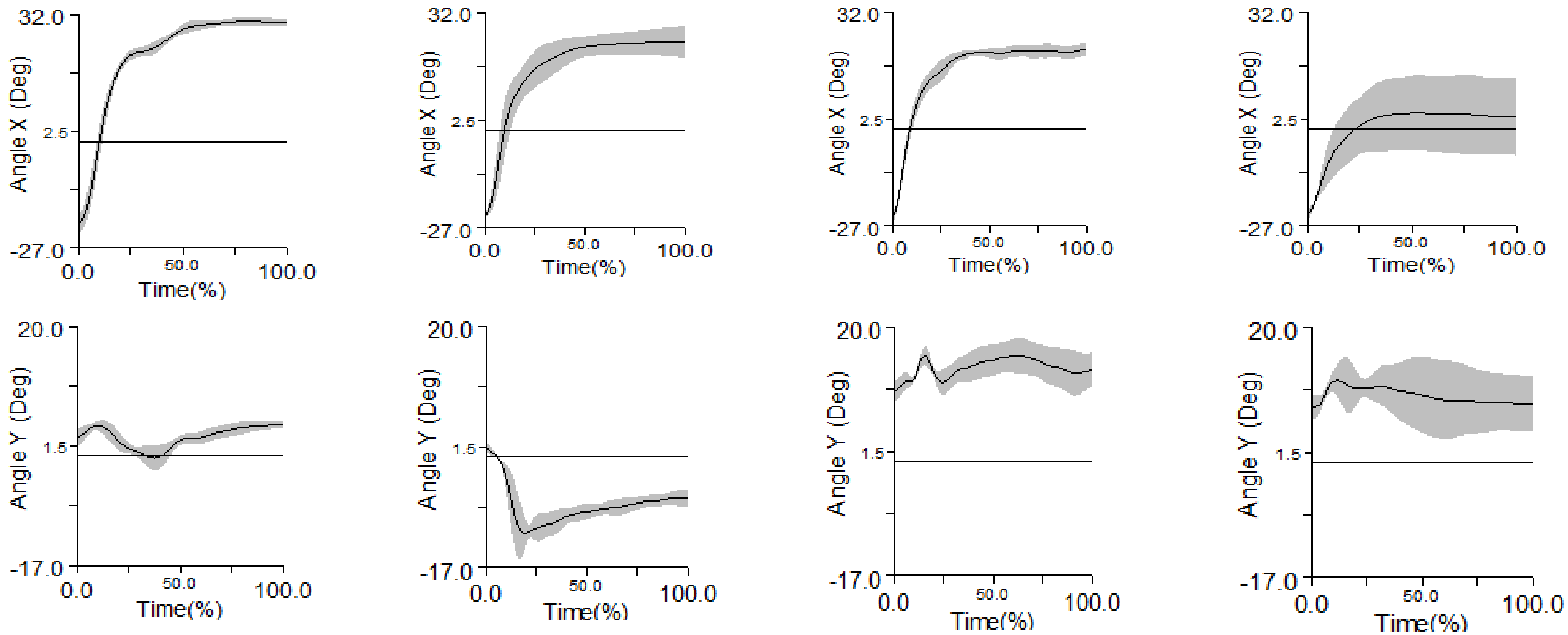
B)

Figure 4. A) Inverted Surface B) Combined Surface.



A) B) C) D)

Figure 5. Representative ensemble mediolateral (top panel), anteroposteior (middle panel) and vertical (bottom panel) ground reaction force curves of a healthy subject in A) double-leg landing, B) single-leg landing on flat surface, C) single-leg landing on inverted surface, and D) single-leg landing on the combined surface.



A) B) C) D)

Figure 6. Representative ensemble ankle dorsiflexion-plantarflexion (top panel) and inversion-everion (bottom panel) angle curves of a healthy subject in A) double-leg landing, B) single-leg landing on flat surface, C) single-leg landing on inverted surface, and D) single-leg landing on the combined surface.

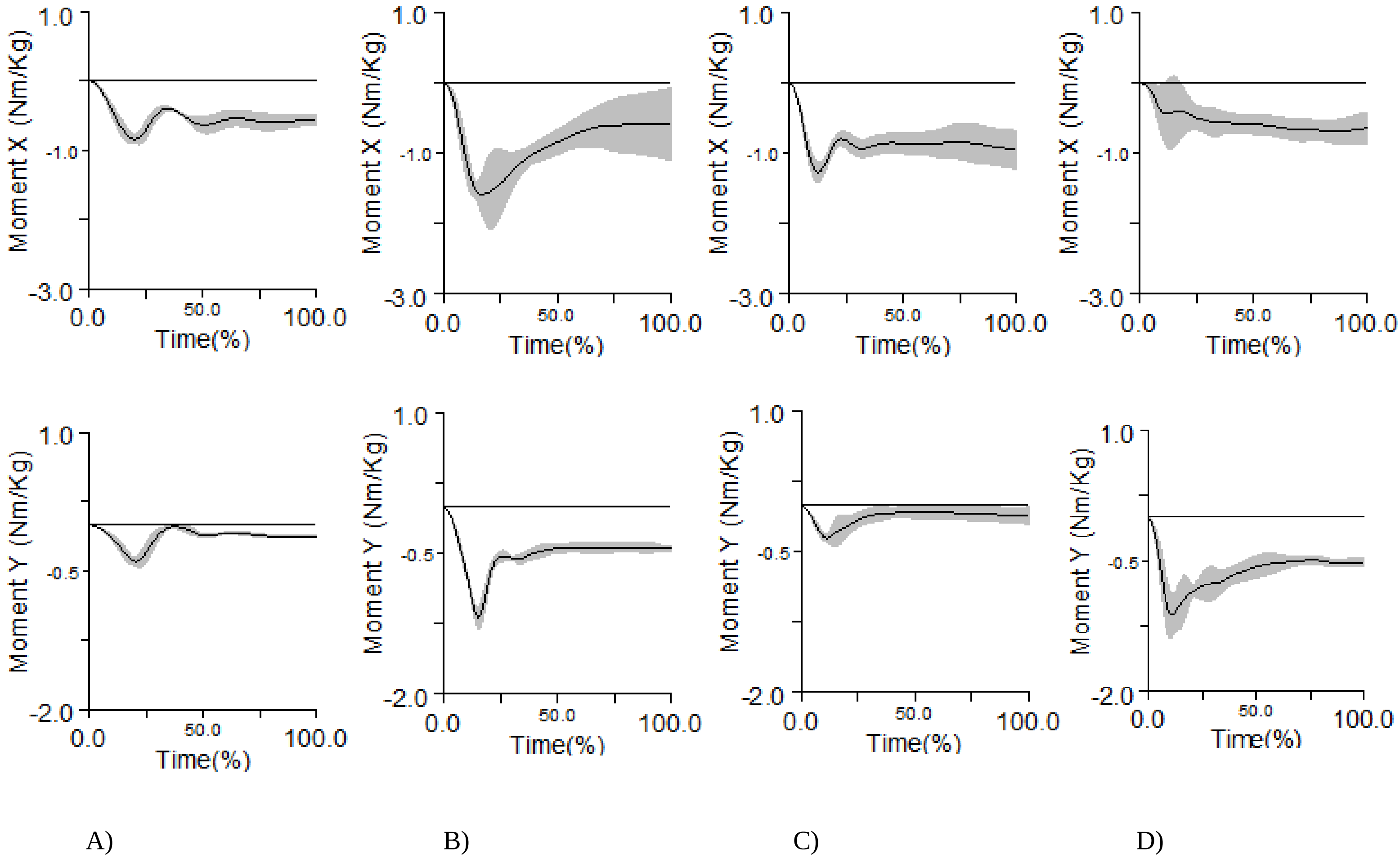


Figure 7. Representative ensemble ankle dorsiflexion-plantarflexion (top panel) and inversion-everion (bottom panel) moment curves of a healthy subject in A) double-leg landing, B) single-leg landing on flat surface, C) single-leg landing on inverted surface, and D) single-leg landing on the combined surface.

Table 1. Ground reaction force and center of pressure variables: mean± SD.

Variables	Healthy				CAI			
	Double-leg Flat	**Single-leg Flat**	**Single-leg Inversion**	**Single-leg Combined**	**Double-leg Flat**	**Single-leg Flat**	**Single-leg Inversion**	**Single-leg Combined**
Peak M-L GRF (BW) [A,C,D]	0.17±0.07	-0.16±0.07	-0.20±0.05	-0.30±0.12	0.17±0.03	-0.19±0.06	-0.19±0.05	-0.28±0.08
Time_Peak M-L GRF (s) [B,C,D]	0.088±0.020	0.081±0.024	0.069±0.013	0.042±0.013	0.069±0.021	0.083±0.013	0.066±0.017	0.038±0.010
Peak vertical GRF (BW) [A,B,D]	1.7±0.4	3.0±0.4	2.7±0.4	2.9±0.3	1.8±0.3	3.0±0.4	2.6±0.2	3.0±0.3
Loading Rate_ (BW/s) [A,B,C,D]	25.9±11.1	40.2±13.6	37.1±9.8	69.3±20.9	36.6±12.4	40.8±10.1	35.5±6.6	70.7±17.6

Note: A - Significant difference between double-leg landing and single-leg landing on flat surface, B Significant difference between single-leg landing on flat and inverted surfaces, C - Significant difference between single-leg landing on flat and combined surfaces, D - Significant difference between single-leg landing on inverted and combined surfaces. M-L - mediolateral, A-P – anteriorposterior

Table 2.Ankle Kinematic and kinetic variables: mean± SD.

Variables	Healthy				CAI			
	Double-leg Flat	**Single-leg Flat**	**Single-leg Inversion**	**Single-leg Combined**	**Double-leg Flat**	**Single-leg Flat**	**Single-leg Inversion**	**Single-leg Combined**
Contact Plantarflexion Angle [A,B]	-23.8±8.3	-27.2±9.3	-25.7±7.2	-26.9±10.7	-12.2±8.2	-25.8±7.9	-21.5±9.7	-25.3±7.0
Dorsiflexion ROM (°) [A,B,C,D]	51.9±9.3	51.7±8.4	45.9±5.8	24.2±7.3	38.5±10.3	46.9±9.2	39.4±10.2	23.1±9.0
Peak eversion/inversion (°) [A,B,C,D]	-2.9±4.8	-14.1±3.1	18.4±4.6	13.1±5.3	-6.0±2.8	-16.8±4.0	14.9±6.2	9.5±6.7
Peak eversion/inversion ROM (°) [A,B,C,D]	-7.9±6.4	-13.1±4.7	13.5±4.6	9.4±2.9	-11.8±8.6	-16.1±8.3	10.6±6.6	9.1±5.3
Peak plantarflexion moment (Nm/kg) [A,C,D]	-1.08±0.48	-1.93±0.65	-1.87±0.72	-1.24±0.55	-0.80±0.28	-1.78±0.39	-1.44±0.40	-0.80±0.33
Peak eversion moment (Nm/kg) [B,C]	-0.31±0.16	-0.29±0.16	-1.16±0.38	-1.14±0.4	-0.39±0.30	-0.26±0.18	-1.09±0.33	-1.09±0.20

Note: A: Significant difference between double-leg landing and single-leg landing on flat surface, B: Significant difference between single-leg landing on flat surface and inverted surface, C: Significant difference between single-leg landing on flat surface and combined surface, D: Significant difference between single-leg landing on inverted surface and combined. EOL – end of landing phase.

Table 3.Knee Kinematic and kinetic variables: mean± SD.

Variables	Healthy				CAI			
	Double-leg Flat	**Single-leg Flat**	**Single-leg Inversion**	**Single-leg Combined**	**Double-leg Flat**	**Single-leg Flat**	**Single-leg Inversion**	**Single-leg Combined**
Flexion ROM (°) [A,D]	-67.1±13.8	-51.9±9.7	-54.4±10.1	-48.2±8.8	-67.3±10.2	-49.7±8.4	-53.3±8.1	-52.5±5.6
Adduction ROM (°) [B,C]	1.5±3.2	2.4±1.2	5.2±3.5	6.3±2.0	6.8±2.8	5.3±2.3	9.4±2.8	8.7±2.4
Peak extension moment (Nm/kg) [A,C,D]	2.2±0.4	3.1±0.3	3.1±0.5	3.4±0.5	2.2±0.5	2.9±0.6	2.8±0.5	3.2±0.6
Peak abduction moment (Nm/kg) [A,B,C]	-0.44±0.30	-1.23±0.31	-1.59±0.50	-1.61±0.30	-0.64±0.10	-1.32±0.110	-1.66±0.15	-1.66±0.15

Note: A: Significant difference between double-leg landing and single-leg landing on flat surface, B: Significant difference between single-leg landing on flat surface and inverted surface, C: Significant difference between single-leg landing on flat surface and combined surface, D: Significant difference between single-leg landing on inverted surface and combined

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APPENDICES

APPENDIX A

Physical Activity Readiness Questionnaire (PAR-Q)

1. Has your doctor ever said that you have a heart condition and recommended only medically supervised physical activity?

   YES **NO**

2. Do you frequently have pains in your chest when you perform physical activity?

   YES **NO**

3. In the past month, have you had chest pain when you were not doing physical activity?

   YES **NO**

4. Do you lose your balance due to dizziness or do you ever lose consciousness?

   YES **NO**

5. Do you have a bone, joint problem that could be made worse by a change in your physical activity?

   YES **NO**

6. Is your doctor currently prescribing drugs(for example, water pills) for your blood pressure or heart condition?

   YES **NO**

7. Do you know any of other reason why you should not do physical activity?

   YES **NO**

Below please provide an explanation for any of the questions to which you answered YES.

____

____

Name: ________________________ Date: ________________________

Signiture: _______________________

APPENDIX B

Demographic Questionnaire

ID number ___________________________ Date (MM/DD/YY): _____/_____/_______

Age (in years) _______________ Shoe Size (US) ________________

Height: ___ Feet ___ Inches or ______ cm Weight: _________lbs or _________ kg

Dominant side (circle one): Right Left

1. Have you had injury with past six months?

   Yes ☐ No ☐

2. What sports do you usually play?

   Basketball ☐ Volleyball ☐ Soccer ☐ Football ☐ Rugby ☐ Tenis ☐

   Other _________________________________

3. Do you exercise more than 1.5 hours per week?

   Yes ☐ No ☐

4. Have you ever had lateral ankle sprain?

   Yes ☐ (Go to Question 5) No ☐to Question 11)

5. If you answer yes to question 1, please write the number of lateral ankle sprains you had:

   Left ankle: last 1 - 12 months _____ 13 - 24 months ______ 25 months or earlier ____

   Right ankle: last 1 - 12 months _____ 13 - 24 months ______ 25 months or earlier____

6. Have you ever have episodes of your ankle "giving way" or "rolling over" after initial ankle sprain?

   Yes ☐ No ☐

7. If answering yes in #6, how many times after initial ankle sprain?

   Left: 1 ☐ 2 ☐ 3 ☐ >3 ☐

   Right: 1 ☐ 2 ☐ 3 ☐ >3 ☐

8. Have you ever have recurrent ankle sprain?

   Yes ☐ No ☐

9. If, answering yes in #8, how many times after initial ankle sprain?

   Left: 1 ☐ 2 ☐ 3 ☐ >3 ☐

   Right: 1 ☐ 2 ☐ 3 ☐ >3 ☐

10. After initial ankle sprain, did you enroll in any rehabilitation program for it?

    Yes ☐ No ☐

11. Have you had major lower extremity surgeries and injuries that may affect the way you walk, run, jump or land (e.g., ACL reconstruction, total/partial knee or hip replacement, bone fractures)?

    Left: Yes ☐ No ☐ Right: Yes ☐ No ☐

    If yes, please provide more details about these injuries.

____

____

____

APPENDIX C

Cumberland Ankle Instability Tool

Cumberland Ankle Instability Tool

Subject#: **ID Number:** **Data:** **Total Score:**

Please tick the ONE statement in EACH question that BEST describes your ankles.

	LEFT	RIGHT	Score
1. I have pain in my ankle			
Never	☐	☐	5
During sport	☐	☐	4
Running on uneven surfaces	☐	☐	3
Running on level surfaces	☐	☐	2
Walking on uneven surfaces	☐	☐	1
Walking on level surfaces	☐	☐	0
2. My ankle feels UNSTABLE			
Never	☐	☐	4
Sometimes during sport (not every time)	☐	☐	3
Frequently during sport (every time)	☐	☐	2
Sometimes during daily activity	☐	☐	1
Frequently during daily activity	☐	☐	0
3. When I make SHARP turns, my ankle feels UNSTABLE			
Never	☐	☐	3
Sometimes when running	☐	☐	2
Often when running	☐	☐	1
When walking	☐	☐	0
4. When going down the stairs, my ankle feels UNSTABLE			
Never	☐	☐	3
If I go fast	☐	☐	2
Occasionally	☐	☐	1
Always	☐	☐	0
5. My ankle feels UNSTABLE when standing on ONE leg			
Never	☐	☐	2
On the ball of my foot	☐	☐	1
With my foot flat	☐	☐	0
6. My ankle feels UNSTABLE when			
Never	☐	☐	3
I hop from side to side	☐	☐	2
I hop on the spot	☐	☐	1
When I jump	☐	☐	0
7. My ankle feels UNSTABLE when			
Never	☐	☐	4
I run on uneven surfaces	☐	☐	3
I jog on uneven surfaces	☐	☐	2
I walk on uneven surfaces	☐	☐	1
I walk on a flat surface	☐	☐	0
8. TYPICALLY, when I start to roll over (or "twist") on my ankle, I can stop it			
Immediately	☐	☐	3
Often	☐	☐	2
Sometimes	☐	☐	1
Never	☐	☐	0
I have never rolled over on my ankle	☐	☐	3
9. After a TYPICAL incident of my ankle rolling over, my ankle returns to "normal"			
Almost immediately	☐	☐	3
Less than one day	☐	☐	2
1–2 days	☐	☐	1
More than 2 days	☐	☐	0
I have never rolled over on my ankle	☐	☐	3

NOTE. The scoring scale is on the right. The scoring system is not visible on the subject's version.

APPENDIX D

Informed Consent Form

Biomechanical Difference between Chronic Ankle Instability Individuals and Healthy Individuals during Landing on Flat, Inverted and Combined Surfaces

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Introduction

You are invited to participate in this research study because you are a healthy active recreational athlete between 18 and 30 years old. There are two subject groups in this study and you may be assigned to either a Chronic Ankle Instability (CAI) group or a healthy group, depending on the results of tests and questionnaires outlined below. The primary purpose of this study is to investigate kinematic and kinetic differences between individuals with CAI, who have both functional and mechanical instability, and healthy subjects. The following activities will be investigated: double-leg drop landing on a flat surface, single-leg drop landing on a flat surface, on an inverted surface and on a combined surface of inversion and plantarflexion. Please ask the study staff to explain any words or information that you do not clearly understand. Before agreeing to be a participant in this study, it is important that you read and understand the following explanation of the procedures, risks, and benefits.

Testing Protocol

The study includes two testing sessions, a screening session and a dynamic testing session, which will be conducted in the Biomechanics/Sport Medicine Lab at the University of Tennessee, Knoxville. Addionally, the screening session may be conducted in the athletic training facility on the UTK campus. During the screening session, you should fill out a Physical Activity Readiness Questionnaire (PAR-Q). Then you complete the Cumberland Ankle Instability Tool (CAIT) for the status of your ankle instability. You will be also asked to fill out a demographic questionnaire. In addition, your ankle laxity will be tested and rated by a certified athletic trainer. Based upon the results of all these tests, it will be determined if you are qualified for the study. If you qualify, you will be asked to attend one additional biomechanical test session in the Biomechanics/Sports Medicine Lab on the UT campus. For the testing session, you will be asked to wear clothing appropriate for exercise which includes spandex short and t-shirt. If you do not have this type of clothing, laboratory spandex short will be provided.

The biomechanical testing session will last approximately 1 to 1.5 hours. Prior to data collection, you will warm up by running for 5 minutes on the treadmill followed by self-stretching for 5 minutes. After the warm up, reflective markers will be placed on both sides of your feet, ankles, legs, knees, thighs, pelvis and trunk in order to capture your movements during landing. You will then perform five successful trials of drop landing from an overhead bar times from 0.3 m in: 1) drop landing on to force platforms with both legs, 2) single-leg drop landing on to the force platform, 3) single-leg drop landing on to the inverted surface, 4) single-leg drop landing on to the combined surface. Healthy subjects will perform single-leg landing with their dominat leg. CAI subjects will perform single-leg landing with the leg with more severe CAI ankle. You will have enough time to practice and become familiar with drop landing conditions and will be given at least a two minute rest between conditions. You are also able to take breaks between trials. Five successful trials will be collected for each of the four testing conditions. You may need to perform up to seven to nine trails in order to get five successful trails. You can end any condition early and are under no obligation to complete the test.

During the testing, biomechanics instruments such as reflective markers and motion capture cameras will be used to obtain measurements. The reflective markers will be placed on your body using double stick medical tape and hook and loop wraps. None of the instruments will impede your ability to engage in normal and effective motions during the test. The cameras will not record pictures of you. If you have any further questions, interests or concerns about any equipment, please feel free to ask the investigator

Potential Risks
Risks associated with this study are minimal because you are recreational athlete who plays landing related sports. The warm-up exercises will allow your body to get ready for the testing protocol. Instruction about drop landing will be given to you. You will be allowed to practice drop landings on the different surfaces. Strips of anti-slip stair tread are adhered to the landing surface to prevent slipping during landing. You may experience delayed onset muscle soreness in which the muscles are sore for a day or two following the testing session. You will be allowed to take breaks between the testing conditions and trials. In addition, the landing height of 30 cm is lower than a typical landing height from a jump in jumping related sports. The similar landing protocol was used for healthy subjects in a previous study in our lab and no adverse effects were observed on the healthy recreational athletes. In addition, a recent published study used a similar landing protocol with CAI subjects. Should any injury occur during the course of testing, standard first aid procedures will be administered as necessary. All tests will be conducted and the equipment will be handled by qualified research personnel in the Biomechanics/Sports Medicine Laboratory. In the unlikely event a physical injury is suffered as a result of participation in this study (during the warm up and testing session), the University of Tennessee does not automatically provide reimbursement for medical care or other compensation and you will be responsible for any medical expenses. If physical injury is suffered in the course of research, or for more information, please notify Xuan Liu (974-2091).

Benefits of Participation
Results from the proposed study may help identify differences in landing strategies between people with CAI and healthy people. This may lead to the development of injury preventions protocols in the future.

Voluntary Participation and Withdrawal
Your participation is entirely voluntary and your refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled. You may withdraw from the study at any time without penalty. 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. Your participation in this study may be stopped if you fail to follow the study procedures or if the investigators feels that it is in your best interest to stop participation.

Compensation
Subjects who complete both manual testing and dynamic testing will be paid $10 to compensate for their time**.**

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. The results will be disseminated in the form of presentations at conferences, and publications in journals. 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.

Contact Information
If you have any questions about the study at any time or if you experience adverse effects as a result of participating in this study, you can contact Xuan Liu at the address above or at 974-2091. Questions about your rights as a participant can be addressed to Compliance Officer in the Office of Research at the University of Tennessee at (865) 974-3466.

Consent Statement
I have read the above information. I agree to participate in this study. I have received a copy of this form.

Subject's Name: ________________Subject's Signature: ____________________ Date: _________

Investigator's Signature: ____________________________ Date: __________ Subject # ______

APPENDIX E

Descriptive Characteristics of Subjects

Table 4. Descriptive Characteristics for healthy subject.

Subject	**Age (years)**	**Height (m)**	**Weight (kg)**	**BMI (kg/m2)**	**Tested Leg**	**Talar Tilt**	**Anterior Drawer**	**CAI Total**	**# of Ankle Sprains**
1	24	1.83	80.50	24.04	Right	1	1	30	0
5	22	1.97	104.33	26.88	Right	1	1	30	0
7	21	1.93	86.18	23.14	Right	1	1	28	0
8	24	1.75	83.01	27.10	Left	1	1	29	0
10	24	1.70	62.50	21.63	Left	1	1	30	0
13	26	1.80	66.00	20.37	Right	1	1	28	0
14	25	1.90	81.65	22.62	Right	1	1	28	0
16	22	1.88	98.43	27.85	Right	1	1	28	0
17	28	1.79	71.44	22.30	Right	1	1	28	0
18	24	1.77	64.64	20.63	Right	1	1	30	0
21	28	1.74	63.96	21.12	Right	1	1	30	0
23	28	1.72	64.18	21.70	Right	1	1	28	0
Mean	24.67	1.82	77.23	23.28		1.00	1.00	28.92	0.00
SD	2.42	0.09	14.17	2.63		0.00	0.00	1.00	0.00

Table 5. Descriptive Characteristics for CAI subjects.

Subject	Age (years)	Height (m)	Weight (kg)	BMI (kg/m2)	Tested Leg	Talar Tilt	Anterior Drawer	CAI Total	# of Ankle Sprains
2	26	1.96	94.80	24.68	Right	2	2.3	23	3
9	27	1.78	79.38	25.05	Right	2	2	22	5
20	23	1.74	73.71	24.35	Right	2	2	24	3
22	22	1.651	78.02	28.62	Right	2	1	24	3
24	24	1.99	90.72	22.91	Right	2	1	24	2
25	22	1.86	73.03	21.11	Right	2	2	24	5
Mean	24.00	1.83	81.61	24.45		2.00	1.72	23.50	3.50
SD	2.10	0.13	9.07	2.50		0.00	0.57	0.84	1.22

APPENDIX F

Kinetic and Kinematic Data

Table 6. Mean Peak M-L GRF for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg Combined
Healthy	1	0.142±0.020	-0.290±0.057	-0.234±0.062	-0.346±0.059
Healthy	5	0.143±0.023	-0.096±0.027	-0.142±0.034	-0.157±0.043
Healthy	7	0.208±0.026	-0.109±0.020	-0.216±0.041	-0.129±0.019
Healthy	8	0.364±0.028	-0.160±0.045	-0.130±0.027	-0.262±0.024
Healthy	10	0.187±0.064	-0.088±0.023	-0.160±0.037	-0.568±0.050
Healthy	13	0.146±0.018	-0.181±0.029	-0.169±0.031	-0.353±0.042
Healthy	14	0.139±0.024	-0.137±0.047	-0.219±0.050	-0.281±0.015
Healthy	17	0.155±0.006	-0.244±0.063	-0.278±0.047	-0.376±0.007
Healthy	18	0.146±0.031	-0.231±0.077	-0.244±0.065	-0.376±0.094
Healthy	21	0.102±0.014	-0.179±0.031	-0.166±0.040	-0.187±0.013
Healthy	23	0.142±0.025	-0.076±0.013	-0.215±0.047	-0.355±0.064
Mean±STD		0.170±0.070	-0.163±0.070	-0.198±0.047	-0.308±0.124
CAI	2	0.155±0.047	-0.232±0.057	-0.186±0.041	-0.331±0.016
CAI	9	0.147±0.030	-0.200±0.037	-0.189±0.031	-0.281±0.029
CAI	20	0.155±0.016	-0.243±0.041	-0.241±0.063	-0.310±0.085
CAI	22	0.154±0.020	-0.218±0.045	-0.249±0.034	-0.391±0.057
CAI	24	0.220±0.045	-0.141±0.038	-0.126±0.024	-0.170±0.022
CAI	25	0.172±0.022	-0.099±0.039	-0.124±0.030	-0.174±0.060
Mean±STD		0.167±0.027	-0.189±0.057	-0.186±0.054	-0.276±0.088

Table 7. Mean Time_Peak M-L GRF for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
Healthy	1	0.095±0.021	0.080±0.003	0.070±0.004	0.043±0.002
Healthy	5	0.114±0.009	0.113±0.015	0.095±0.008	0.068±0.010
Healthy	7	0.117±0.021	0.096±0.005	0.084±0.006	0.053±0.005
Healthy	8	0.073±0.004	0.086±0.006	0.079±0.003	0.044±0.004
Healthy	10	0.067±0.017	0.114±0.002	0.059±0.006	0.030±0.002
Healthy	13	0.080±0.009	0.078±0.002	0.065±0.002	0.030±0.002
Healthy	14	0.112±0.015	0.084±0.020	0.075±0.005	0.057±0.006
Healthy	17	0.098±0.022	0.081±0.006	0.058±0.004	0.033±0.002
Healthy	18	0.088±0.005	0.066±0.003	0.060±0.010	0.041±0.015
Healthy	21	0.059±0.021	0.071±0.003	0.068±0.003	0.037±0.004
Healthy	23	0.071±0.005	0.025±0.002	0.050±0.003	0.029±0.002
Mean±STD		0.088±0.020	0.081±0.024	0.069±0.013	0.042±0.013
CAI	2	0.081±0.003	0.080±0.010	0.073±0.002	0.033±0.002
CAI	9	0.060±0.030	0.079±0.003	0.066±0.006	0.036±0.003
CAI	20	0.069±0.021	0.074±0.005	0.066±0.008	0.034±0.006
CAI	22	0.060±0.031	0.076±0.003	0.056±0.008	0.035±0.003
CAI	24	0.042±0.005	0.082±0.009	0.042±0.005	0.033±0.009
CAI	25	0.104±0.031	0.109±0.008	0.093±0.008	0.059±0.003
Mean±STD		0.069±0.021	0.083±0.013	0.066±0.017	0.038±0.010

Table 8. Mean Peak vertical GRF for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
Healthy	1	1.671±0.261	3.683±0.097	3.641±0.262	3.330±0.194
Healthy	5	1.412±0.199	2.475±0.216	1.968±0.017	2.907±0.187
Healthy	7	1.702±0.263	2.398±0.175	2.563±0.138	2.310±0.186
Healthy	8	2.126±0.106	3.041±0.304	2.727±0.249	3.096±0.319
Healthy	10	1.610±0.317	2.834±0.193	2.752±0.117	2.604±0.132
Healthy	13	2.332±0.133	3.210±0.244	2.960±0.249	3.341±0.159
Healthy	14	1.244±0.135	2.550±0.233	2.637±0.166	2.696±0.177
Healthy	17	1.599±0.153	2.867±0.094	2.680±0.223	3.153±0.186
Healthy	18	1.952±0.320	3.290±0.137	2.486±0.165	2.908±0.313
Healthy	21	1.173±0.118	2.836±0.293	2.679±0.154	2.527±0.325
Healthy	23	2.159±0.307	3.237±0.147	2.977±0.158	3.227±0.163
Mean±STD		1.725±0.379	2.947±0.392	2.734±0.403	2.918±0.347
CAI	2	1.981±0.200	3.290±0.211	2.618±0.151	3.387±0.261
CAI	9	2.491±0.115	3.258±0.090	2.406±0.231	3.211±0.214
CAI	20	1.917±0.033	3.221±0.240	2.906±0.213	3.231±0.108
CAI	22	1.530±0.216	2.914±0.224	2.400±0.158	2.842±0.070
CAI	24	1.673±0.201	3.088±0.337	2.694±0.140	2.501±0.259
CAI	25	1.488±0.338	2.141±0.069	2.403±0.153	2.865±0.192
Mean±STD		1.847±0.373	2.985±0.436	2.571±0.207	3.006±0.329

Table 9. Mean Loading Rate_Peak vertical GRF for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
Healthy	1	20.034±3.000	47.699±2.484	48.894±2.134	72.670±7.994
Healthy	5	13.832±2.743	20.606±2.921	19.118±4.264	44.945±5.539
Healthy	7	18.490±4.123	25.912±2.017	28.895±2.805	38.019±6.092
Healthy	8	29.057±3.639	37.080±3.154	32.760±3.163	65.135±7.553
Healthy	10	31.703±3.253	38.155±2.924	37.552±4.407	81.075±5.072
Healthy	13	39.193±3.500	45.590±5.259	40.886±4.752	98.588±8.566
Healthy	14	14.236±2.202	27.605±3.000	33.272±3.625	45.002±5.832
Healthy	17	19.732±2.080	36.795±3.406	40.767±4.910	87.249±5.329
Healthy	18	31.295±6.017	51.502±3.349	33.802±5.118	70.039±22.589
Healthy	21	18.835±3.110	41.142±4.518	36.720±3.289	61.407±13.143
Healthy	23	48.868±6.373	69.617±2.489	55.924±7.067	97.832±5.725
Mean±STD		25.934±11.117	40.155±13.607	37.144±9.781	69.269±20.944
CAI	2	48.276±15.618	44.803±10.127	33.956±3.223	91.886±4.035
CAI	9	50.369±4.488	43.505±2.412	33.224±5.185	78.442±10.418
CAI	20	31.213±2.546	44.538±5.269	39.249±2.895	81.902±13.676
CAI	22	30.891±7.346	40.364±5.100	37.198±2.531	72.296±8.066
CAI	24	40.864±14.177	50.411±10.025	44.461±3.863	54.221±10.356
CAI	25	17.691±6.928	21.183±1.795	24.869±3.147	45.333±3.805
Mean±STD		36.551±12.355	40.801±10.146	35.493±6.600	70.680±17.617

Table 10. Mean Contact Plantarflexion Angle for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
Healthy	1	-26.307±2.724	-28.478±1.113	-27.307±2.429	-35.443±0.757
Healthy	5	-31.044±5.675	-37.268±0.629	-34.841±3.244	-37.583±1.002
Healthy	7	-21.435±2.276	-24.367±1.195	-24.810±1.193	-31.012±1.922
Healthy	8	-37.470±1.818	-41.698±4.529	-40.649±3.165	-42.940±1.552
Healthy	10	-15.545±9.033	-20.695±1.149	-20.642±1.679	-6.724±4.825
Healthy	13	-26.647±6.748	-38.314±1.168	-27.590±2.491	-24.307±1.814
Healthy	14	-29.793±3.324	-27.508±1.487	-25.899±1.578	-34.621±0.881
Healthy	17	-27.584±1.577	-26.909±3.280	-19.201±3.163	-21.843±1.658
Healthy	18	-21.115±2.287	-23.433±0.773	-24.647±1.317	-23.792±1.632
Healthy	21	-15.818±1.916	-22.086±2.391	-23.798±0.555	-23.830±1.159
Healthy	23	-8.531±3.392	-8.875±2.139	-13.758±1.898	-14.273±2.583
Mean±STD		-23.754±8.257	-27.239±9.292	-25.740±7.274	-26.943±10.671
CAI	2	-4.305±17.588	-28.296±3.258	-26.042±2.719	-15.522±2.756

Table 11. Continued.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
CAI	9	-8.685±1.855	-28.793±1.010	-21.039±6.693	-26.509±0.548
CAI	20	-22.675±3.532	-30.618±2.216	-24.894±3.355	-24.454±4.914
CAI	22	-11.081±1.134	-27.894±1.107	-21.125±2.394	-22.993±3.622
CAI	24	-4.557±4.391	-9.811±3.356	-3.562±1.775	-25.262±2.170
CAI	25	-21.997±2.876	-29.300±1.326	-32.227±1.335	-37.147±0.288
Mean±STD		-12.217±8.247	-25.785±7.883	-21.482±9.688	-25.314±6.978

Table 12. Mean Dorsiflexion ROM for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
Healthy	1	50.428±3.915	47.726±1.526	39.129±0.793	24.703±2.331
Healthy	5	56.538±5.500	52.876±1.928	48.897±2.792	31.346±3.486
Healthy	7	54.798±2.600	51.409±1.974	47.887±3.687	30.944±2.414
Healthy	8	47.440±0.395	52.122±2.530	41.907±3.638	21.803±3.178
Healthy	10	37.798±7.435	49.111±4.551	45.642±4.835	10.077±4.636
Healthy	13	56.950±6.262	59.359±2.538	46.473±4.686	21.423±4.087
Healthy	14	62.260±0.545	61.239±2.622	45.332±1.618	33.537±1.744
Healthy	17	68.323±2.110	63.358±6.345	53.878±4.692	26.558±2.607
Healthy	18	51.256±2.870	47.495±4.141	46.536±1.871	23.979±2.028
Healthy	21	45.971±4.615	51.430±3.941	54.565±3.154	28.030±2.287
Healthy	23	38.735±1.562	32.344±5.324	35.042±1.259	13.566±3.208
Mean±STD		51.863±9.286	51.679±8.379	45.935±5.766	24.179±7.282
CAI	2	35.266±2.108	48.048±0.611	37.372±2.398	8.001±4.375
CAI	9	38.413±1.933	56.335±2.537	43.964±4.566	27.968±4.375
CAI	20	50.291±2.046	51.846±6.902	42.512±5.010	24.608±5.618
CAI	22	32.622±2.420	46.861±1.590	35.979±3.622	18.377±3.338
CAI	24	24.063±3.534	29.362±3.398	23.051±2.106	25.268±1.826
CAI	25	50.293±3.594	48.897±3.032	53.697±3.196	34.205±4.234
Mean±STD		38.491±10.311	46.891±9.234	39.429±10.179	23.071±8.992

Table 13. Mean Peak Eversion/Inversion for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
Healthy	1	-5.841±1.910	-15.396±0.896	15.914±1.780	11.501±1.619
Healthy	5	0.157±1.127	-12.409±0.922	18.519±2.114	16.327±1.419
Healthy	7	-2.151±0.274	-11.989±3.303	15.361±1.992	14.043±1.485
Healthy	8		-16.293±0.498	12.566±2.198	8.281±1.445
Healthy	10	-0.663±2.932	-16.657±1.549	17.692±2.362	6.757±2.456
Healthy	13	-11.065±1.026	-17.627±1.903	20.871±3.255	12.449±1.911
Healthy	14	2.336±2.794	-14.631±1.142	13.470±0.795	4.691±0.528
Healthy	17	3.771±0.946	-6.449±1.010	29.015±2.424	21.937±1.168
Healthy	18	-0.698±1.630	-14.027±1.864	17.722±0.917	13.351±2.693
Healthy	21	-5.920±1.365	-14.893±1.236	22.381±2.875	20.263±3.040
Healthy	23	-8.512±0.712	-15.091±1.521	19.380±1.929	14.303±2.708
Mean±STD		-2.858±4.803	-14.133±3.053	18.445±4.586	13.082±5.285
CAI	2	-4.741±1.177	-15.147±1.157	13.847±2.360	8.652±2.912

Table 14. Continued.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
CAI	9	-4.962±0.557	-13.863±0.769	20.119±2.167	10.817±1.417
CAI	20	-4.272±0.761	-12.791±2.263	17.202±1.295	15.498±3.737
CAI	22	-6.216±0.771	-22.379±0.924	4.184±0.728	-3.163±2.352
CAI	24	-4.370±2.430	-15.368±1.523	21.123±1.089	14.029±1.601
CAI	25	-11.491±0.915	-21.247±1.054	13.108±2.171	11.125±2.249
Mean±STD		-6.009±2.775	-16.799±4.009	14.931±6.171	9.493±6.662

Table 15. Mean Peak Eversion/Inversion ROM for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
Healthy	1	-12.419±1.928	-15.743±1.080	8.867±2.544	4.825±0.801
Healthy	5	-4.334±1.887	-18.000±1.225	14.726±2.650	11.918±1.383
Healthy	7	-15.153±3.241	-16.450±4.659	5.166±2.058	7.112±0.942
Healthy	8		-9.544±1.808	16.141±2.364	11.666±3.184
Healthy	10	-8.514±7.468	-14.122±2.562	16.094±2.115	6.386±3.020
Healthy	13	-9.996±1.525	-6.639±1.486	20.150±2.914	11.249±1.946
Healthy	14	4.383±4.018	-3.520±3.191	17.417±2.599	9.668±2.072
Healthy	17	-2.342±1.571	-14.217±2.293	15.936±1.059	10.809±1.585
Healthy	18	-3.386±2.022	-15.579±1.381	7.278±2.224	5.010±3.647
Healthy	21	-12.665±2.230	-17.758±1.212	14.439±3.478	12.645±4.393
Healthy	23	-14.866±1.532	-13.007±1.779	12.125±3.343	11.609±2.927
Mean±STD		-7.929±6.358	-13.144±4.674	13.485±4.616	9.354±2.947
CAI	2	-5.922±1.498	-15.866±2.320	7.166±1.275	4.029±4.664

Table 16. Continued.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
CAI	9	-10.055±1.422	-13.840±2.206	12.212±2.281	5.620±1.093
CAI	20	-14.776±2.041	-11.948±2.177	10.552±1.507	12.075±4.936
CAI	22	-8.470±2.515	-13.808±1.387	11.479±0.371	10.120±2.693
CAI	24	-4.210±3.235	-8.774±2.392	21.160±1.809	17.821±4.762
CAI	25	-27.392±2.929	-32.228±0.832	0.885±1.301	4.987±3.211
Mean±STD		-11.804±8.465	-16.077±8.264	10.576±6.649	9.109±5.305

Table 17. Mean Peak Plantarflexion Moment for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
Healthy	1	-1.407±0.200	-2.863±0.104	-3.283±0.372	-1.751±0.117
Healthy	5	-2.104±0.251	-2.895±0.145	-2.453±0.174	-2.323±0.154
Healthy	7	-1.569±0.317	-2.517±0.298	-2.536±0.101	-1.775±0.096
Healthy	8	-1.441±0.161	-2.382±0.599	-2.578±0.156	-1.614±0.235
Healthy	10	-0.570±0.134	-1.130±0.068	-1.725±0.178	-0.615±0.009
Healthy	13	-0.805±0.148	-1.476±0.261	-1.349±0.129	-0.765±0.153
Healthy	14	-0.812±0.181	-2.068±0.178	-1.635±0.127	-1.213±0.196
Healthy	17	-0.940±0.096	-1.187±0.129	-1.164±0.128	-0.793±0.131
Healthy	18	-0.875±0.082	-1.801±0.318	-1.279±0.162	-0.687±0.198
Healthy	21	-0.674±0.103	-1.417±0.162	-1.324±0.104	-1.030±0.106
Healthy	23	-0.684±0.114	-1.514±0.180	-1.223±0.211	-1.026±0.071
Mean±STD		-1.080±0.481	-1.932±0.650	-1.868±0.721	-1.236±0.554
CAI	2	-0.493±0.153	-1.832±0.302	-1.420±0.217	-0.462±0.305
CAI	9	-0.869±0.171	-1.952±0.123	-0.942±0.010	-0.715±0.070
CAI	20	-0.793±0.208	-1.540±0.331	-1.520±0.154	-0.788±0.136
CAI	22	-0.625±0.064	-1.407±0.126	-1.036±0.173	-0.686±0.098
CAI	24	-1.315±0.258	-2.458±0.114	-1.953±0.145	-0.705±0.116
CAI	25	-0.721±0.138	-1.514±0.132	-1.770±0.240	-1.426±0.124
Mean±STD		-0.803±0.283	-1.784±0.390	-1.440±0.398	-0.797±0.327

Table 18. Mean Peak Eversion Moment for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
Healthy	1	-0.313±0.092	-0.435±0.117	-1.475±0.139	-1.294±0.135
Healthy	5	-0.189±0.021	-0.381±0.033	-0.801±0.126	-1.081±0.094
Healthy	7	-0.294±0.050	-0.310±0.041	-0.923±0.098	-0.969±0.099
Healthy	8	-0.055±0.022	-0.049±0.020	-0.332±0.053	-0.374±0.068
Healthy	10	-0.272±0.041	-0.047±0.003	-1.123±0.156	-0.577±0.130
Healthy	13	-0.674±0.091	-0.317±0.084	-1.676±0.485	-1.773±0.184
Healthy	14	-0.298±0.053	-0.579±0.018	-1.457±0.127	-1.257±0.078
Healthy	17	-0.340±0.051	-0.262±0.067	-1.455±0.203	-1.433±0.108
Healthy	18	-0.429±0.078	-0.412±0.042	-1.206±0.129	-1.312±0.155
Healthy	21	-0.196±0.033	-0.139±0.008	-1.147±0.127	-1.295±0.191
Healthy	23	-0.395±0.038	-0.286±0.044	-1.207±0.199	-1.225±0.159
Mean±STD		-0.314±0.158	-0.293±0.164	-1.164±0.376	-1.145±0.390
CAI	2	-0.994±0.270	-0.604±0.250	-1.458±0.143	-1.180±0.346
CAI	9	-0.256±0.043	-0.171±0.038	-1.042±0.190	-1.170±0.152
CAI	20	-0.373±0.073	-0.267±0.088	-1.223±0.141	-1.344±0.181
CAI	22	-0.202±0.043	-0.189±0.034	-0.764±0.057	-0.764±0.115
CAI	24	-0.386±0.127	-0.157±0.037	-1.402±0.096	-1.203±0.149
CAI	25	-0.178±0.108	-0.152±0.035	-0.671±0.197	-0.864±0.103
Mean±STD		-0.398±0.304	-0.257±0.175	-1.093±0.327	-1.088±0.223

Table 19. Mean Flexion ROM for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
Healthy	1	-50.264±4.906	-34.490±0.641	-38.595±3.637	-31.927±3.133
Healthy	5	-44.194±5.362	-34.651±2.396	-50.606±3.137	-47.851±2.945
Healthy	7	-75.911±4.029	-58.171±7.489	-62.523±1.479	-56.976±3.515
Healthy	8	-54.778±3.686	-46.306±9.972	-44.529±4.890	-37.765±5.516
Healthy	10	-81.576±1.439	-57.371±6.742	-50.455±3.534	-47.648±6.878
Healthy	13	-65.984±5.128	-52.861±3.416	-57.445±4.738	-47.562±5.778
Healthy	14	-65.773±1.917	-55.019±3.033	-46.766±2.227	-45.174±1.679
Healthy	17	-80.212±1.476	-64.749±6.765	-66.578±4.161	-51.750±3.441
Healthy	18	-70.888±4.576	-57.023±4.230	-65.230±5.944	-58.921±8.960
Healthy	21	-87.959±8.852	-58.383±4.660	-68.212±5.229	-61.263±7.084
Healthy	23	-61.082±2.202	-51.501±1.312	-47.545±3.125	-43.634±5.414
Mean±STD		-67.147±13.812	-51.866±9.723	-54.408±10.070	-48.225±8.830
CAI	2	-65.681±4.670	-40.901±4.872	-44.280±3.505	-43.516±6.872

Table 20. Continued.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
CAI	9	-62.890±3.787	-62.191±2.738	-56.453±5.815	-54.191±6.378
CAI	20	-79.610±3.540	-49.938±7.168	-51.086±2.668	-48.998±4.513
CAI	22	-70.576±2.602	-49.723±1.096	-59.367±3.583	-52.177±2.764
CAI	24	-50.539±5.827	-40.128±5.076	-44.494±3.641	-56.835±6.816
CAI	25	-74.623±5.104	-55.115±3.006	-64.014±6.916	-59.141±4.922
Mean±STD		-67.320±10.187	-49.666±8.420	-53.282±8.067	-52.476±5.636

Table 21. Mean Adduction ROM for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
Healthy	1	3.399±0.953	2.573±0.572	2.093±2.991	5.166±3.761
Healthy	5	1.897±0.572	1.655±0.532	4.405±1.514	7.374±1.999
Healthy	7	2.655±0.965	2.959±0.914	9.081±1.348	6.947±1.681
Healthy	8	0.840±0.271	4.048±2.006	9.533±3.924	8.429±1.002
Healthy	10	1.370±1.613	2.572±0.621	5.415±1.334	7.307±1.232
Healthy	13	2.794±1.888	3.475±1.164	6.455±1.123	5.584±1.640
Healthy	14	-7.449±5.146	1.697±3.149	0.976±1.225	4.827±1.528
Healthy	17	2.563±0.568	3.595±2.448	8.390±3.888	4.570±0.411
Healthy	18	0.819±0.904	0.953±0.705	3.232±0.978	5.117±1.056
Healthy	21	2.615±0.307	0.323±0.284	-0.830±1.118	3.411±1.740
Healthy	23	4.670±1.646	2.822±1.933	8.116±1.591	10.556±1.231
Mean±STD		1.470±3.165	2.425±1.153	5.170±3.500	6.299±2.048
CAI	2	7.313±1.214	4.867±1.419	8.367±0.896	7.350±0.780
CAI	9	2.480±1.325	2.610±0.466	5.330±1.153	5.697±0.701
CAI	20	5.367±1.177	3.179±0.958	7.247±0.836	7.141±1.256
CAI	22	10.868±0.858	4.885±1.364	11.579±1.222	9.424±5.145
CAI	24	6.556±4.393	8.263±2.384	11.191±0.760	11.635±1.122
CAI	25	8.442±1.623	7.734±1.670	12.452±3.321	11.013±0.665
Mean±STD		6.838±2.838	5.256±2.315	9.361±2.812	8.710±2.356

Table 22. Mean Peak Extension Moment for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
Healthy	1	2.016±0.197	2.824±0.124	2.415±0.317	2.580±0.040
Healthy	5	1.832±0.180	2.496±0.297	2.507±0.236	2.950±0.216
Healthy	7	3.181±0.312	3.259±0.337	3.664±0.204	3.560±0.270
Healthy	8	2.263±0.037	2.870±0.229	2.674±0.209	3.216±0.214
Healthy	10	1.850±0.591	3.348±0.043	3.261±0.261	4.422±0.154
Healthy	13	2.354±0.147	2.798±0.155	2.842±0.108	3.224±0.176
Healthy	14	2.379±0.220	3.793±0.120	3.855±0.109	3.792±0.309
Healthy	17	2.224±0.108	3.234±0.122	3.206±0.221	3.803±0.232
Healthy	18	2.154±0.369	3.313±0.243	2.864±0.240	3.420±0.468
Healthy	21	1.610±0.164	3.203±0.058	3.228±0.190	3.153±0.255
Healthy	23	2.314±0.307	3.073±0.175	3.063±0.192	3.322±0.248
Mean±STD		2.198±0.409	3.110±0.350	3.053±0.452	3.404±0.489
CAI	2	2.455±0.292	2.814±0.115	2.344±0.119	3.122±0.206
CAI	9	2.793±0.094	2.862±0.114	2.734±0.332	3.398±0.154
CAI	20	2.258±0.186	3.005±0.119	3.144±0.082	3.657±0.295
CAI	22	1.425±0.037	2.259±0.061	2.091±0.139	2.325±0.184
CAI	24	2.321±0.207	3.911±0.324	3.518±0.215	3.974±0.245
CAI	25	2.016±0.197	2.685±0.253	2.670±0.274	2.861±0.216
Mean±STD		2.211±0.462	2.923±0.547	2.750±0.520	3.223±0.588

Table 23. Mean Peak abduction Moment for individual subjects: Mean ± STD.

Group	Subject	Double-leg Flat	Single-leg Flat	Single-leg Inversion	Single-leg combined
Healthy	1	-0.626±0.153	-1.563±0.506	-1.694±0.218	-1.974±0.388
Healthy	5	-0.338±0.069	-1.310±0.196	-1.507±0.173	-1.636±0.113
Healthy	7	-1.112±0.336	-1.632±0.155	-2.653±0.158	-1.867±0.135
Healthy	8	-0.014±0.027	-0.753±0.164	-1.123±0.068	-1.162±0.139
Healthy	10	-0.143±0.157	-0.846±0.032	-1.473±0.103	-1.814±0.135
Healthy	13	-0.513±0.101	-1.357±0.129	-1.679±0.182	-1.580±0.168
Healthy	14	-0.228±0.106	-1.179±0.188	-1.144±0.153	-1.551±0.171
Healthy	17	-0.519±0.084	-1.531±0.124	-1.922±0.335	-1.814±0.114
Healthy	18	-0.354±0.122	-1.371±0.151	-1.392±0.070	-1.441±0.114
Healthy	21	-0.311±0.034	-0.811±0.238	-0.875±0.040	-1.033±0.055
Healthy	23	-0.652±0.206	-1.153±0.091	-2.019±0.274	-1.882±0.218
Mean±STD		-0.437±0.299	-1.228±0.311	-1.589±0.493	-1.614±0.304
CAI	2	-0.635±0.213	-1.518±0.494	-1.589±0.062	-1.753±0.086
CAI	9	-0.749±0.119	-1.292±0.069	-1.555±0.269	-1.638±0.179
CAI	20	-0.657±0.076	-1.291±0.174	-1.621±0.212	-1.453±0.287
CAI	22	-0.550±0.131	-1.182±0.135	-1.509±0.277	-1.710±0.165
CAI	24	-0.508±0.068	-1.298±0.116	-1.752±0.123	-1.527±0.013
CAI	25	-0.744±0.182	-1.320±0.107	-1.921±0.174	-1.876±0.135
Mean±STD		-0.641±0.099	-1.317±0.110	-1.658±0.153	-1.659±0.154

VITA

Xuan Liu was born in Renqiu, China on November 30, 1988 to the parents of Ruiqiang Liu and Minying Wang. She is the only daughter. She attended elementary school and junior high school in Renqiu. She graduated from No. 3 high school in Huabei Oilfield in 2007. From there, she went to Beijing Sport University where she was introduced to sports medicine and biomechanics. Xuan Liu completed Sport Rehabilitation and Health program with Professor Hui Liu, which was an exciting and challenging experience and pushed her into continuing her education abroad. She obtained a Bachelor of Science degree from Beijing Sport University in the year of 2011 and accepted a graduate teaching assistantship at The University of Tennessee, Knoxville, in the physical Education and Activities Program. Xuan Liu graduated with a Master of Science degree in exercise science with a concentration in biomechanics in the year of 2013.