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Comparison of Methods Simulating the Ankle Sprain Mechanism:Inversion Drop Test and Landing on a Slanted Surface

Qingjian Chen
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To the Graduate Council:

I am submitting herewith a thesis written by Qingjian Chen entitled "Comparison of Methods Simulating the Ankle Sprain Mechanism:Inversion Drop Test and Landing on a Slanted Surface." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Exercise Science.

Dr. Songning Zhang, Major Professor

We have read this thesis and recommend its acceptance:

Dr. Clare Milner, Dr. Eugene Fitzhugh

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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

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ABSTRACT

The purposes of this study were to investigate the kinematics of two ankle brace testing protocols. They were drop landing on a slanted surface and the inversion drop test. Difference in kinematics and ground reaction forces of drop landing wearing an ankle brace on flat and lateral slant surfaces were also investigated. Eleven healthy subjects performed five trials in each of six dynamic movement conditions. They were an ankle inversion drop test on the inversion platform, drop landing from 0.45 m onto slant surface, and drop landing from 0.45 m onto flat surface with and without an ankle brace. A 7-camera motion analysis system was used to obtain the three-dimensional kinematics. In addition, a force platform was used to measure the ground reaction forces (GRF) during drop landing. A 2 × 2 (brace × movement) repeated measures ANOVA was used to evaluate selected variables for inversion drop test and landing on slant surface ($p < 0.05$). In addition, the differences between landing on the flat and slant surfaces were examined using a 2 × 2 (brace × surface) repeated measures ANOVA. The results showed that the slant surface landing resulted in significantly earlier maximum inversion angle occurrence. Significantly higher maximum eversion and inversion velocities were also found in the slant surface landing compared to the inversion drop. In the comparison of landing on the slant surface and flat surfaces, the results showed that slant surface landing led to smaller 1st and 2nd peak vertical and horizontal GRFs, greater maximum inversion and its range of motion (ROM), and smaller dorsiflexion ROM. The results suggest that the slant surface landing simulate ankle sprain mechanism better than the inversion drop test. Subjects adopted a softer landing strategy when landing onto the flat surface and a stiffer strategy when landing onto the slanted surface.

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CHAPTER I

INTRODUCTION

The ankle is one of the most traumatized body sites in sports and accounts for 10-30% of all sports injuries [15]. Of those ankle injuries, the lateral ankle ligaments are the most frequently injured site in the body and are commonly associated with lateral ankle sprain. It was estimated that approximately $318 to $914 is spent for treatment of each sprain leading to an aggregate cost of $2 billion in the United States [40]. In the past, taping was the common method used to restrict ankle range of motion (ROM) for the prevention of first time and recurrent ankle sprain. Nowadays, it has become a norm to use an ankle brace instead of other methods in prevention and rehabilitation of ankle sprains. Ankle braces provide multiple benefits over taping, which include reduced costs, ease of application, ability to retighten during physical activity, and fewer adverse effects on athletic performance than other methods [17, 35, 39].

Research investigating the restricting effects of ankle braces has typically utilized a rapidly induced inversion condition using an ankle inversion platform commonly referred to as a trapdoor (a platform allowing the sudden drop of one surface in order to simulate ankle inversion) [1, 2, 6-8, 13, 14, 37]. Drop landing on a slant surface has also been used [45]. However the trapdoor device is limited to inversion, but a lateral ankle sprain is caused by a combination of ankle inversion and plantar flexion. Most lateral ankle sprains occur in landing on an uneven surface from a jump [1, 2, 6-8, 13, 14, 37]. During landing, the ankle joint is naturally placed into a plantarflexed and inverted position before touchdown. Greater impact loading is applied to the body and the ankle joint during landing, therefore greater inversion loading is applied to the ankle joint compared to using the trapdoor device. A landing onto a slanted surface would create a more realistic simulation, therefore possibly provide more realistic results compared to the trap door testing condition [45].

In the findings of trapdoor studies, ankle ROM is significantly reduced with the application of an ankle brace both in passive inversion and rapid inversion conditions as well as in plantarflexion/dorsiflexion and internal/external rotation [13]. Maximum inversion angle after landing, and maximum and mean inversion velocities have been found to be reduced while wearing an ankle brace [2, 6, 7, 14]. Besides these, ankle braces have been proven to keep individual's ankle neutral position during free fall phase of trapdoor landing without bodyweight loading, therefore causing decreased maximum inversion angle at loading phase after contact[2, 14]. One common conclusion from ankle brace studies is that a semi-rigid design restricts ankle ROM most effectively during ankle inversion movement, without adverse effect on athletic performance [17, 30, 31]. The inversion tilting angles of the inversion drop test used in ankle brace studies are 22° [2], 30° [1, 13, 14], and 35° [6, 7]. In general, 30° is the most common tilting angle used [1, 5, 8, 9, 24, 44].

In contrast to ankle brace studies using inversion drop testing, a very limited number of studies employed drop landing in their experimental protocol [18, 26, 44, 45]. Among these, only one study actually employed a landing testing protocol on a slant surface [45]. Venesky found a greater ankle eversion torque, and knee external rotation torque wearing an ankle brace during drop landing compared to wearing no brace condition [45]. A slant surface of 20° was used in the study and this angle is slightly smaller than the common inversion angle of 30° used in most of inversion drop device studies. A landing onto a slanted surface creates a more realistic simulation of a lateral ankle sprain situation [45]. McCaw examined soft and stiff landing styles using drop landing wearing ankle braces and found a significantly reduced maximum ankle angular velocity while wearing an ankle brace. Hodgson found that the peak vertical ground reaction force and loading rate at toe contact significantly increased and the ankle angle at toe contact significantly decreased during drop landing onto a flat surface wearing an ankle brace [18]. Different from those studies, Ubell and colleagues tested the success rates of a specific jump landing task wearing two semi-rigid braces and one lace-up brace with a fulcrum affixed to the plantar surface of the landing foot [44]. The semi-rigid braces showed significantly greater success rates in keeping balance for three seconds after one foot landing with a 24° inversion fulcrum affixed to the heel of the shoes compared to the lace-up brace and no brace condition.

Statement of Problem

The primary purpose of this study was to investigate kinematic differences in two ankle brace testing protocols, drop landing (on a slant surface) and inversion drop device, in restriction of ankle inversion.

The secondary purpose was to investigate differences in kinematics and ground reaction forces during drop landing while wearing an ankle brace on surfaces with different lateral surface inclination.

Possible outcomes of this study include a recommendation of a more realistic ankle inversion injury testing protocol for future research.

Hypothesis

The main hypothesis was that the drop landing onto a slant surface would result in similar peak inversion angle, but greater angular velocity, contact plantarflexion angle, contact dorsiflexion velocity and maximum dorsiflexsion velocity compared to the inversion drop testing condition.

The secondary hypothesis was that landing on the slant surface would introduce smaller peak vertical GRFs and greater horizontal peak GRFs, and greater peak inversion angle compared to the flat surface landing condition.

Wearing an ankle brace would reduce the differences in above testing protocols.

Delimitations

This study had the following delimitations:

1. Eleven apparently healthy subjects were selected from a convenience sample of student and surrounding population of the University of Tennessee, Knoxville. Each subject was free from major lower extremity injuries.

2. Each subject performed five trials in all six conditions.

3. Kinematic data were collected 3 seconds using a seven-camera motion analysis system at 240 Hz.

4. GRF data were collected for 3 seconds bilaterally during each trial using two force platforms at 1200 Hz.

Limitations

This study had the following limitations:

1. All subjects were not required to have previous experience of using an ankle brace.

2. Accuracy of kinematic and ground reaction force data were limited by the accuracy of the 3D kinematic systems and force platforms, and accuracy of marker placement on the subject. However, every effort was made to complete the process adherent to sound practice of

biomechanical principles and strict instructions of the manufacturers, and through sufficient practice.

CHAPTER II

LITERATURE REVIEW

The primary purpose of this study was to investigate kinematic differences in two ankle brace testing protocols, drop landing (on a slant surface) and inversion drop device, in restriction of ankle inversion. The secondary purpose was to investigate differences in kinematics and ground reaction forces during drop landing while wearing an ankle brace on surfaces with different lateral surface inclination. Possible outcomes of this study include a recommendation of a more realistic ankle inversion injury testing protocol for future research. Literature regarding anatomy, symptom, and grade of ankle injury, epidemiology of lateral ankle sprain injury, external support and benefits of ankle brace, kinematic and kinetic characteristics of ankle brace in dynamic movement from inversion trapdoor and drop landing experimental protocols prospective were reviewed in this chapter.

Anatomy, Symptoms, and Grade of Ankle Injury

The ankle complex is made up of four bones: tibia, fibula, talus, and calcaneus [29]. The tibia is the major bone of the lower leg and its distal end forms the medial malleolus, the medial ankle [29]. The fibula is the smaller of the two bones in the lower leg and its distal end forms the lateral malleolus, the outer ankle [29]. The talus is the top tarsal bone that articulates with the distal tibia and fibula to form the talocrural joint (ankle joint, which has 2 articulations: talotibial and talofibular joints) [29]. Distal talus forms an articulation called the subtalar joint (talocalcaneal joint) with the calcaneus. The dorsi- and plantar-flexion originates from the talocrural joint and the inversion and eversion occur mainly in the subtalar joint. The ankle complex has many ligaments holding different bones together. At the lateral side there is a lateral collateral ligament complex that has three primary ligaments: anterior talofibular, calcaneofibular, and posterior talofibular ligament [29]. The anterior talofibular ligament is relatively small running from the anterior aspect of the fibula forward to attach to the talus. It is the most often injured ligament [29]. The second most commonly injured ligament is calcaneofibular ligament locating behind the anterior talofibular ligament [29]. It runs from the fibula to the calcaneus. The calcaneofibular ligament functions as a back-up ligament to the anterior talofibular ligament. The posterior talofibular ligament which runs from the fibula back to the talus, is rarely injured in a lateral ankle sprain [29]. All these three ligaments are not as strong as the deltoid ligaments on the medial side of the ankle [29].

A lateral ankle sprain usually occurred in a mechanism combined with excessive inversion and a plantar flexed ankle [23]. At the time of injury, athletes usually experience a pop or "snap". Those with more severe sprains will be unable to bear weight. During physical examination, swelling and bruising are localized to the lateral ankle, and the injured ligament is tender to palpation. Stress tests such as the anterior drawer and talar tilt can be performed to confirm the diagnosis of a lateral ankle sprain and grade injury severity [23]. A grade one sprain represents a stretch injury of the ligament(s). There is minimal to no swelling and stress tests demonstrate pain but no laxity. A grade two sprain represents a partial tear of the ligament(s). There is moderate pain and swelling with some laxity on stress test [23]. A grade three sprain represents a complete tear of the ligament(s). There is significant pain, swelling and bruising, and inability to ambulate, and gross laxity on stress test [23].

Epidemiology of Lateral Ankle Sprain Injury

Ankle is one of the most traumatized body sites in sports accounting for 10 - 30% of all sports injuries [15]. In an epidemiology study of injuries in 15 sports among NCAA athletes, spring football (1.34 per 1,000 athlete- exposures) and men's basketball (1.30 per 1000 athlete-exposure) had the highest rates of ankle ligament sprains for games and practices combined from 1988 to 2005. Women's ice hockey (0.14 per 1,000 athlete- exposures), men's ice hockey (0.23 per 1,000 athlete-exposure), and men's baseball (0.23 per 1,000 athlete-exposure) had the lowest injury rates [19]. Men's football had the highest number of ankle ligament injuries (9,929) followed by men's basketball (3,205) and women's basketball (2,446). Through a nationally representative sample obtained by High School Reporting Information Online system, an injury surveillance system during the school year 2005-2006, an estimated 326,396 ankle injuries occurred. This resulted in an injury rate of 5.23 ankle injuries per 10,000 athlete-exposure [28]. In sports featuring body contact, swift changes of direction and high frequency of landing and cutting, ankle injuries rates are even higher. Boys' basketball has highest injury rate of 7.74 per 10,000 athlete-exposure, followed by girls' basketball (6.93) and boys' football (6.52).

During competitive game settings in team sports, the injury rates are higher. In NCAA Men's basketball, participants were more than twice as likely to sustain an ankle ligament sprain in a game as in a practice with an injury rate of 2.33 versus 1.06 per 1,000 athlete-exposure [12]. In NCAA Men's football, the total number of ankle ligament sprains was 4,799 during fall games compared to 5,011 during fall practices [11]. The absolute number of ankle ligament injury during game situation was slightly lower than that of the fall practice situation. The injury rate for ankle ligament sprain was 15.6 % of all body injuries during fall games compared to 11.8% during fall practices [11]. The participants suffered an ankle ligament sprain almost 12 times more during fall games than during fall practices situation with injury rates of 5.39 per 1,000 exposures and 0.45 per 1,000 exposures, respectively [11]. In high school sports, ankle injuries also occurred more often during game with a rate of 9.35 per 10,000 athletes-exposure compared to practice with a rate of 3.63 [28].

Different from the hip and knee joints which have various injury types, the ankle is known for its high occurrence of the single type of injury, sprain. Garrick found that 85% of ankle injuries are the sprain to the lateral ligaments [16]. In a systematic review on ankle injury and ankle sprain studies, ankle sprains account for between 80% and 100% of all ankle injuries sustained [15]. Of these ankle injuries, approximately 77% were located at the lateral side. Based upon the NCAA injury surveillance data in 16 years in 15 sports, more than 27,000 ankle ligament sprains were reported, yielding an average of approximately 1,700 per year [19]. Assuming the sample represents about 15% of the total NCAA institutions, this equates to an annual average of more than 11,000 ankle sprains in these 15 sports [19].

Direct consequences of ankle sprains include the cessation of training and competition. In the epidemiology study of NCAA men's basketball injuries [12], ankle ligament sprain is the second leading type of injury resulting in the loss of 10+ days of activity time. Knee internal derangement is the leading type of injuries. During the game situation, the total number of ankle ligament sprains resulting in loss of 10+ days of activity time was 123, and 16.2% of these were severe injuries [12]. During practices, the total number of ankle ligament sprains was 250 and 17.5% of these were severe injuries [12]. During fall games, the total number of ankle ligament sprains was 1,032, of which 12.4% were severe injuries. During fall practices, the total number was 1,014, and 9.6% of them were severe injuries [11]. In a 2-year cohort study among female Greek professional basketball players [21], fifty of the 204 participants sustained ankle injuries, of which 32 players suffered an ankle sprain. These 32 players missed a total of 224.4 training and game sessions resulting an average of 7.01 sessions per injury [21]. In the ankle injury surveillance study of high school athletes, 51.7% of ankle injuries caused athletes to miss less than 7 days of activity, followed by 33.9% with a loss of 7 to 21 days of activity, and 10.5% with more than 22 days of activity loss [28].

It was reported by Staples that only 58.7% of sprained ankles completely recovered after 10.4 years of follow-up [41]. Pain, swelling, weakness, and instability of the ankle are major residual symptoms after ankle sprains. The cost of medical care and rehabilitation program as well as the "time loss" can be a huge burden for both athletes and sport teams. In a cost analysis study, it was found that the cost of treating these injuries ranged from $318 to $914 per sprain, with an annual aggregate cost of $2 billion in the US [40]. Therefore the prevention of ankle injury during training, game situations and even recreational activities becomes a priority in sports medicine.

External Support and Benefits of Ankle Brace

The major factor causing the lateral ankle sprain is the combination of excessive plantar flexion and inversion of the ankle [46]. For this reason various external support systems for the ankle joint have been designed, aiming at restricting excessive ankle ROM, especially inversion and eversion. Several methods of ankle protection have evolved, with the most commonly used external support systems being adhesive taping, orthoses (braces), and specially designed shoes or a combination of those [46].

The most common methods of ankle protection are ankle taping and brace [3, 4]. However, the following disadvantages make taping less ideal as the support and the prevention of ankle sprains: taping is easily loosen during exercise, technical and complicated taping techniques are required by professional clinicians, it is not reusable and causes skin irritation. Ankle braces have become more popular in prevention of recurrent ankle sprains and rehabilitation. Ankle braces are reusable, relatively cheap, easily applied, and can be retighten by athletes themselves. Several studies have shown that braces reduce the incidence of ankle sprains [35, 39], and restrict ankle range of motion as effectively as tape and do not lose this effectiveness with exercise [17]. Other studies have also reported that these orthotic devices do not adversely affect athletic performance [17, 30, 31]. Sitler et al. conducted a randomized clinical study among 1,601 cadets during two years intramural basketball seasons. They found that the ankle sprain injury rate was 1.6 per 1,000 athlete-exposure for the players wearing a semi-rigid orthosis while the injury rate was 5.2 sprains per 1,000 athlete-exposure for the groups of unprotected ankles [39]. Greene conducted a study comparing the effectiveness of athletic taping and a semi-rigid orthosis before, during, and after exercise by testing vertical jump ability while using each support method [17]. Results showed that an initial inversion-eversion ROM restriction was diminished to 15% from 41% after 3 hours of exercise with taped ankle, while braced ankles showed a reduction from 42% to only 37% using a semi-rigid orthosis [17]. The orthosis showed a loss in limiting eversion range of motion, but no significant inversion restriction loss due to exercise was observed. Both orthosis and taping had no adverse effect on the vertical jumping. Alt and his colleagues studied mechanical, neuromuscular, and thermal effects aspects of four different tape application techniques before and after exercise [1]. The results showed that approximately 35% of the initial maximum inversion amplitude was significantly decreased by ankle taping compared to the unprotected ankle joint prior to exercise. Comparing pre-exercise and 30 min post-exercise, less than 14% loss of restriction was found for the nonelastic adhesive tape with the short wraping technique [1].

Pienkowski tested the effect of ankle braces on vertical jumping, standing long jumping, cone running, and shuttle running among 12 high school basketball players, and showed braces had no significant effects on athletic performance [31]. Paris also failed to find significant differences in the results of speed, balance, agility with taping or ankle braces [30]. The function of the ankle brace may include mechanical support to preload the ankles and maintain the ankles in a proper anatomical position at impact. In addition, the proprioception improvement at the ankle joint can also be accomplished through ankle bracing [3].

Ankle braces produce greater benefits than taping, however, this can vary greatly depending on the design that is being used. Three commonly used ankle braces are soft (lace-up, no rigid plastic parts), rigid (rigid plastic parts embracing the heel, the sole and the shank), and semi-rigid (rigid plastic parts on medial and lateral sides of the ankle connected by soft material in a stirrup design) [14]. By comparing appearance, comfort, adverse effects, and whether it is loosen or not following exercise through both questionnaire and research investigation, the semi-rigid brace has been proven to be the most effective [13, 39, 44]. The semi-rigid brace is therefore recommended as the leading orthosis to restrict inversion movement with the least adverse effect of athletic performance [42].

Kinematic and Kinetic Characteristics of the Braced Ankle in Dynamic Movements

Studies on kinematics and kinetics of braced ankles have typically used an inversion drop platform called a trap-door platform (a wooden box allowing the sudden drop of one surface in order to simulate ankle inversion) [1, 2, 6-8, 13, 14, 37], drop landing on a slant surface [45], and cutting movement [5, 48]. Most studies have analyzed two dimensional (2D) aspects of kinematics and kinetics associated with ankle braces [7]. A few studies have addressed the three dimensional (3D) kinematics of inversion drop on the trap-door [2, 33], where fewer focused on 3D kinematics and kinetics of landing onto slant surface wearing ankle orthoses [45].

Eils and his colleagues used a trapdoor to determine the efficacy of 10 different ankle braces and provided valuable information for each ankle brace [13]. The authors used the same data to analyze the major functions of the ankle braces during protection of ankle inversion [14]. Cordova and his colleagues conducted a series of studies examining relationships between the ankle brace and electromyographical (EMG) latency of peroneus longus, the stretch reflex amplitude of peroneus longus, the Hoffmann reflex effect of peroneus longus, and rearfoot motion [6-8, 37]. These studies used a trapdoor to exert ankle inversion while capturing the EMG activity of the major eversion muscle. In addition to these, a relatively unique one was to study the ground reaction force and EMG wearing ankle braces in lateral cutting [5]. Anderson provided comprehensive analysis of kinematic data on the restriction of lace-up ankle brace using a trapdoor device and provided supplemental information on non-rigid ankle braces [2]. On the other hand, Venesky et al. examined ankle and knee joint kinetics and kinematics with and without the ankle brace during drop landing and determined how ankle brace affected other lower extremity joints [45]. Hodgson et al. compared kinetic and lower extremity kinematic differences with and without the ankle brace during a flat surface drop landing [18]. McCaw and his colleagues analyzed how ankle braces affect ankle joint kinematics during soft and stiff drop landings [26]. Ubell evaluated the efficacy of three ankle braces during a jump landing task [44].

Inversion Drop Test Using a Trapdoor Device

Eils et al. tested 24 subjects wearing 10 ankle braces including rigid, semi-rigid and soft types during passive and rapidly induced inversion tests [13]. The inversion drop test was performed with a sudden inversion of 30º and with most of the body weight applied to the involved foot. Passive range of motions of plantar/dorsiflexion, inversion/eversion, and internal/external rotation were collected. A dynamic inversion loading test focused on ankle inversion/eversion. A customized goniometer was affixed to the inside of the shoe to measure the hindfoot inversion angle. The results of passive restriction tests showed that all braces restricted ROM in three directions significantly compared to the no brace condition. The ankle braces showed most significant reduction in inversion compared to other directions with 37% least effective (soft, Kalassy S®) models and 57% most effective (semi-rigid, Air Gel®) models in passive ROM restrictions respectively. For eversion and plantarflexion, rigid and semi-rigid braces were more effective than soft braces. For the inversion drop testing conditions, all braces restricted maximum inversion significantly with 51% and 85% of reduction for the most (Semi-rigid, Aircast®) and least effective (Soft, Kalassy® and Fibulo Tape®) models respectively, compared to the no-brace condition. The semi-rigid ankle brace with stirrup design and stable/plastic reinforcements was the most effective brace in restricting inversion while not limiting athletic performance. In order not to limit athletic performance, the semi-rigid brace should be the best choice [13].

Eils et al. did a follow up analysis on the data from the above study [14]. The landing phase was subdivided into the free fall phase without bodyweight loading and the loading phase after contact with weight bearing. Inversion angles were derived and averaged, mean velocities for the inversion movement were calculated as the ratio of the inversion angle and the time duration. The results showed that all braces significantly restricted average inversion angles and maximum inversion angles ranging between 13° and 23° for the free fall phase, and 19° and 33° for the loading phase after contact. The most effective restriction of motion was provided by the semi-rigid braces. Differences between the 30° tilting angle (free fall) and the maximum inversion angle (loading phase after contract) were in the range of 6° to 10° for the brace conditions and the no-brace condition, respectively. A high correlation (r=0.99) was found between the 30° tilting angle and maximum ankle inversion angle. All braces reduced mean inversion velocities significantly with mean peak inversion velocities ranging between 260 °/s to 445 °/s compared to 557 °/s in the no-brace condition. It was suggested that ankle braces provide protection against excessive ankle inversion before bodyweight loading prior to impact. This leads to a decreased moment arm at the subtalar joint at ground contract and therefore a smaller inversion torque [14].

Cordova et al. conducted a long-term (8 weeks) study on the effects of the ankle brace on peroneus longus muscle latency [6]. Twenty active subjects without lower extremity injuries for at least 12 months participated in this study. Three conditions including one control without brace, one semi-rigid brace (Active Ankle Training brace, Active Ankle Systems, Inc, Louisville, KY), and one lace-up brace (McDavid 199, McDavid Knee Guard, Chicago, IL) were randomly assigned to be tested in a 35° trapdoor drop test at the pre-treatment testing date and the post-treatment date eight weeks after the brace application. The results showed no significant changes before and after eight weeks, indicating external ankle support neither facilitated nor inhibited the peroneus longus muscle latency among normal subjects [6]. Cordova and his colleagues also examined the amplitude of the peroneus longus stretch reflex and showed that the lace-up brace (67.1) had a significantly higher % maximum of stretch reflex amplitude ($P<0.05$) than the semi-rigid brace (57.9) and control groups (59.0) at the initial testing [8]. The peroneus longus stretch reflex amplitude increased after 8-week use of the semi-rigid brace compared with the lace up and control groups ($P<0.05$). The findings of both studies disagreed with the thought that long term use of external ankle stabilizers may diminish neuromuscular response and weakness of major surrounding muscles [6, 8]. On the other hand, the use of the semi-rigid brace increased the amplitude of the peroneus longus stretch reflex after eight weeks application [8].

Besides muscle EMG activity, Cordova and his colleagues also conducted a two-dimensional study on rearfoot motion wearing a semi-rigid brace (Active Ankle T2, Active Ankle Systems, Inc., Louisville, KY), a lace-up brace (McDavid A101, McDavid Knee Guard Inc., Chicago, IL), and control (no brace) in a 35° inversion drop test on a trapdoor device [7]. A video-based motion analysis system was used to measure subtalar joint inversion angle and inversion velocity. The statistical analysis showed that the semi-rigid brace significantly reduced average subtalar inversion angle (10.71°) and average inversion velocity (279.29 °/s) compared to the lace-up (14.69° & 351.39 °/s) and control conditions (27.13° & 565.55 °/s). In addition, a significantly reduced average inversion velocity was found for the lace-up condition in comparison with the control condition. The semi-rigid brace was shown to be superior in subtalar joint inversion restriction, with the lace-up ranked second [7].

Anderson examined the effectiveness of lace-up bracing (Non-rigid subtalar stabilizer STS brace) in ankle inversion restriction before and after exercise among 15 women and 15 men [2]. A 22° inversion trapdoor was used in the study. A few highlights of this study were the use of the nonfunctional brace as a placebo treatment, and testing conducted pre- and post-exercise. Similar to the Eils's study on inversion drop using a trapdoor [14], the dropping phase was subdivided into free fall and loading phases after impact. Major variables included the duration of the free-fall and loading phase, the calcaneal inversion ROM for each phase collected by a conductive plastic electrogoniometer (Type Megatron UP10), and the maximum vertical ground reaction force. The maximum calcaneal inversion angle was significantly reduced from 27.4° to 18.3° for the overall drop phase in the lace-up brace condition. The overall inversion phase time was lengthened from 0.14 s to 0.18 s. The peak inversion velocity was reduced from 324.6 °/s to 165.2 °/s during the loading phase, and from 278.7 °/s to 183.0 °/s for the overall drop. Even after exercise, the non-rigid brace still provided significant reductions in the calcaneal inversion angle and velocity, although some effects were reduced [2]. The facts that an ankle brace mainly restricts the foot inversion during the free fall phase are in agreement with the findings of Elis's study [14].

<u>Drop Landing onto a Slanted Surface</u>

Venesky studied ankle and knee biomechanics of the unilateral drop landing from 30 cm height on to a 20° slanted surface for 24 non injury college students with and without an ankle brace (Active Ankle-T2, Cramer Products Inc, Gardner, KS) [45]. Major dependent variables were peak ankle inversion-eversion torque, peak knee varus-valgus torque, and peak knee internal-external rotation torque. The results showed that subjects wearing an ankle brace were more likely to have greater ankle eversion torque ($F_{1,23}$ =19.75, P<0.01), and knee external rotation torque ($F_{1,23}$ = 4.33, P< 0.05) compared to the no brace condition. The peak knee valgus torque was similar in the brace condition. Increased ankle eversion torque suggested that the ankle brace acted like a supplemental ankle lateral ligament to resist inversion torque during landing. Loading experienced in drop landing in this study was referred as axial loading meaning that more vertical than horizontal force is applied to the lower extremity compared to a cutting movement in which loading is mainly not axial [45]. Wearing an ankle brace may not cause significant changes in valgus knee torque during axial loading. However if ankle brace was evaluated in cutting movement, the results of knee valgus torque might have been different. It was further suggested that knee rotational torque is associated with rotation of thigh, shank, and foot.

Hodgson and his colleagues examined the difference between wearing a semi-rigid ankle brace and no brace on vertical ground reaction forces (VGRF) and kinematic data of the bilateral drop landing from 0.61 m height onto a force platform of 12 college volleyball players [18]. The dropping height was determined by the mean height of the maximum vertical jump. During the brace condition, the subjects were required to wear ankle braces (Active Ankle T2 brace, Active Ankle Systems, Inc, Louisville, KY) on both ankles. Kinematic data were collected using a 8-camera kinematic system at 120 Hz (Peak Performance Technologies) and the ground reaction force data were captured using a single force platform sampled at 600 Hz (Model SN 3242, Advanced Mechanical Technology, Inc, Newton, Mass). Kinetic data included first peak VGRF at toe contact (P1) and second peak GRF at heel contact (P2), times to P1 and P2, loading rate of P1 and P2. The results showed a significant increase in P1, P1 loading rate, and a significant decrease in ankle angle at P1 during the braced condition compared to the no braced condition. It was concluded that the increased VGRF was due to the decreased ankle range of motion while wearing a semi-rigid ankle brace.

McCaw and his colleagues examined sagittal ankle joint kinematics with different ankle stabilizers in landing [26]. Fourteen injury-free college students were asked to perform bilateral soft and stiff step landing from a 59 cm height on to a force platform wearing one lace-up ankle brace (Swede-O-Universal, North Branch, MN), two semi-rigid ankle braces (Aircast Sport Stirrup, Summit, NJ & Cramer Active Ankle, Gardner, KS), athletic ankle tape (Coach Athletic Tape, Johnson & Johnson, Skillman, NJ), and no ankle brace (control). The results regarding landing styles suggested that there was a 5° ankle angle difference at maximum knee flexion between soft (25.5°) and stiff (19.0°) landings, and a 6° ankle joint ROM difference between soft (38.3°) and stiff (31.9°) landing styles. The results regarding ankle stabilizers suggested that there were 2 - 4° less plantarflexion ankle joint angle at touchdown, 2 - 3° less dorsiflexion ankle angle at maximum knee flexion, and 5 - 6° less ankle joint ROM in the Swede-O, Aircast, and tape conditions compared to the Active Ankle and control conditions. A significantly lower maximum ankle angular velocity was found in all stabilizer conditions compared to the control condition. The authors indicated that ankle braces may adversely affect normal ankle joint kinematics during landing as well as energy absorption of the lower extremity chain.

Ubell conducted research to evaluate the effect of ankle braces on the prevention of ankle inversion [44]. A fulcrum that can cause a maximum shoe sole inversion of 24° was installed onto the testing NIKE low-top basketball shoes to provide a dynamic ankle inversion perturbation. All participants were blind to whether this fulcrum system was installed or not during the one leg jump from a platform for a distance of 60cm onto a force platform. They were asked to keep balanced after landing for at least 3 seconds for a successful trial during three testing sessions: two semi-rigid braces (Aircast Sport Stirrup, Aircast, Inc., Summit, New Jersey & Bledsoe Ultimate Ankle Brace, Bledsoe Brace Systems, Grand Prairie, Texas,) and one lace-up brace (Swede-O Ankle Lok, Swede-O-Universal, Inc., North Branch, Minnesota). Peak ground reaction force was monitored to allow 10% variability from 2.0 to 2.2 body weight (BW) during jump landing. It was found that two semi-rigid braces showed significantly greater success rates in keeping balance at 52% for the Bledsoe brace and 46% for the Aircast brace, respectively when compared to 24% success rate for the unbraced condition [44]. It was suggested that the loading and 24° ankle tilting angle were realistic enough to mirror the real ankle lateral inversion injury situation. Two semi-rigid ankle braces were stiffer than the lace-up brace.The stiffer the ankle brace, the better the brace can resist inversion loading. The ankle braces were found to reduce the initial ankle inversion angle before the body is loaded, and therefore reduce the maximum inversion angle at the end of the loading phase [14]. Ankle braces positioned the foot and ankle in a more neutral posture, and thereby restricted maximum inversion angle after loading [14].

CHAPTER III

METHODOLOGY

The primary purpose of this study was to investigate kinematic differences in two ankle brace testing protocols, drop landing (on a slant surface) and inversion drop device, in restriction of ankle inversion. And the secondary purpose was to investigate differences in kinematics and ground reaction forces during drop landing while wearing an ankle brace on surfaces with different lateral surface inclination. Meanwhile provide scientific explanations about advantages and disadvantages of each testing protocol. This chapter describes the procedures used in this study and will include the following sections: participants, instrumentation, experimental procedures, and data and statistical analysis.

Participants

A total of 11 healthy subjects (age: 24.6 ± 3.5 years, height: 1.70 ± 0.10 m, mass: 65.6 ± 14.9 kg), 6 females and 5 males, from the University of Tennessee, Knoxville and the surrounding areas was recruited to participate in this study. 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 advised 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.

Instrumentation

Anthropometric Measures: Body mass (kg) and height (m) of participants were measured using a calibrated physician's scale. In addition to height and weight, ankle width with and without ankle braces were measured using a caliper (Anthropometer, model 01291, Lafayette instrument company, Lafayette, Indiana).

3D High-speed Video System: A seven-camera motion analysis system (240 Hz, Vicon *PEAK* Motion Analysis Inc., UK) was used to obtain the three-dimensional (3D) kinematics during the test. Reflective anatomical and tracking markers were placed on both sides of the foot, ankle, and leg, knee, thigh and pelvis during testing. Anatomical markers were placed on the left and right iliac crest, left and right greater trochanters, left and right lateral epicondyles, left and right medial epicondyles, left and right lateral malleolus, left and right medial malleolus, left and right fifth metatarsal heads, and left and right first metatarsal heads. A set of four tracking markers on a rigid shell was placed on the thighs and legs; a set of two tracking markers was placed on both sides of the pelvis. For the foot, three tracking markers were placed directly on the posterior and lateral heel.

Force Platform: Two force platforms (1200 Hz, American Mechanical Technology Inc, MA.) were used to measure the ground reaction forces (GRF) and the moments of force during testing in drop landing movements.

Inversion platform: A trap door platform (91.5 cm (L) x 46 cm (W) x 20 cm (H)) was used to induce an inversion movement upon a release of a locking system that is pneumatically controlled. The device has two electromechanical switches that catch the release of the inversion platform surface and the contact of the platform surface with the ground separately. The switching signals are combined as one analog channel and sampled by the Vicon system. The participant stood with the foot bilaterally on a separate and raised platform. The surface of the tested side was dropped laterally to an inversion angle of 25º, without prior knowledge of the participant.

Slant surface: A slant surface (45.72 cm (L) × 22.86 cm (W) × 11.43 cm (H)) with a 25° slope was constructed and mounted on one of the right side force platform with double sided tape. It was used in the landing conditions. The device allows the ankle to be inverted 25° after the drop landing from the overhead bar. The subject landed bilaterally with the right foot on the center of the slant surface and the left foot on the left force platform. To facilitate landing without slipping after contact, strips of sand paper were affixed to the top slant surface. The 25º slant surface was within the tolerance of participants in our pilot testing work.

Flat surface: A flat surface (40 cm (L) × 40 cm (W) × 4 cm (H)) wooden board was mounted on the top of the left force platform to provide support for the left leg in order to avoid imbalance after drop landing.

Adjustable overhead bar: An adjustable overhead bar controlled by an electrical hoist was hung from the ceiling at a height 0.45 m above the center of the slant surface as measured from the mid-heel of the participant's right leg. The subject was instructed to hold the bar with both hands at shoulder width and release the hands to land with the right foot on the slant surface and the left foot on the left force platform.

Ankle Brace and Lab Shoes: One ankle brace (Element, DeRoyal Industries, Inc, TN.) with three sizes (small, medium and large) was used on the right side of the participant in the test conditions described below. A pair of standard lab running shoes was worn by the participant throughout testing.

Experimental Procedures

The study included one testing session conducted in the Biomechanics/Sports Medicine Lab at the University of Tennessee. The subject was asked to fill out questionnaires about his/her injury history, physical activity, and subject demographic information prior to the test. The participant started with a standard warm-up of running on a treadmill at 3.4 miles/h for 4 minutes, and stretching. Ankle widths were measured before the brace and no-brace conditions.

During the dynamic testing session, the participant performed five trials in each of six dynamic movement conditions: 1) an ankle inversion drop test on the inversion platform with and 2) without ankle brace, 3) drop landing from 0.45 m on to the slanted surface with and 4) without ankle brace, and 5) drop landing from 0.45 m on to flat surface with and 6) without ankle brace. The participant was given ample time to practice and become familiar with the ankle brace and the testing movements prior to the actual testing. Due to the need for two separate static calibration trials, one with the ankle brace and one without the brace, the order of brace conditions (with or without brace) was first randomized. Once the order of brace conditions was determined, the testing movements (inversion drop, drop landing on slant surface and flat surface) were then randomized within the condition. The inversion drop testing condition was performed with participants standing upright on the platform with bodyweight distributed evenly between the two feet with the arms kept in front of the body. The inversion drop was initiated by the data collector through a pneumatically controlled switch when subject was ready after standing on the platform without prior knowledge of the subject. A successful trial was a trial where the subject was able to keep balance after dropping with the right foot inverted.

All drop landing trials were performed from the over-head bar from a 0.45 m height measured from the mid-heel to the landing surface (either the force platform or the slant surface). In the landing on to the slant surface, the subject was asked to land in a normal technique so that the left foot landed on the left force platform while the right foot landed on the middle of the slant surface. To be consistent, the subject was asked to look at front during landing without looking down. The landing on to the flat surface was done with the right foot landing on the right force platform instead with the slant surface removed from the force platform. A successful trial was a trial where the subject landed without losing balance in any direction.

Three-D kinematic data, GRF data and switching signal were collected simultaneously. However, GRF data were analyzed only for drop landing conditions.

Data and Statistical Analysis

Three-D markers position data and GRF data were smoothed using a 4^{th}-order Butterworth low-pass filter at cutoff frequencies of 8 Hz and 50 Hz respectively. Kinematic and GRF data of the inversion drop testing was analyzed from the contact of the trapdoor surface to the ground to 500 ms after the contact. The drop landing movement was analyzed from the foot contact to the maximum knee flexion for the drop landing conditions. Three-D kinematic and GRF variables were computed in Visual3D. Critical events were determined using a customized computer program (MS VisualBasic 6.0) from the output of Visual3D. The variables of interest include peak vertical and mediolateral GRF, contact ankle inversion/eversion angle & velocity, maximum inversion angle/eversion angle & velocity, inversion/eversion ROM, contact plantarflexion angle, contact and maximum dorsiflexion angle & velocity, times to these peak GRFs & kinematic variables, and other relevant kinematic variables. The GRF data were normalized to body weight (BW).

In order to examine the effects of bracing on differences between the inversion drop testing and landing on the slant surface, a 2 × 2 (brace × movement) repeated measures analysis of variance (ANOVA) was used to evaluate interested variables, with an alpha level of 0.05 (SPSS 15.0, SPSS Inc., Chicago, IL). In addition, surface effects during landing on the flat and slant surfaces were examined using a 2 × 2 (brace × surface) repeated measures ANOVA.

CHAPTER IV

COMPARISON OF METHODS SIMULATING THE ANKLE SPRAIN MECHANISM:

INVERSION DROP TEST AND LANDING ON A SLANTED SURFACE

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ABSTRACT

The purposes of this study were to investigate the kinematic differences of two ankle brace testing protocols. They were drop landing on a slant surface and the inversion drop test. Differences in kinematics and ground reaction forces of drop landing wearing an ankle brace on flat and lateral slant surfaces were also investigated. Eleven healthy subjects performed five trials in each of six dynamic movement conditions. They were an ankle inversion drop test on the inversion platform, drop landing from 0.45 m on to slant surface, and drop landing from 0.45 m on to flat surface with and without an ankle brace. A 7-camera motion analysis system was used to obtain the three-dimensional kinematics. In addition, a force platform was used to measure the ground reaction forces (GRF) during drop landing. A 2 × 2 (brace × movement) repeated measures ANOVA was used to evaluate selected variables for inversion drop test and landing on slant surface ($p < 0.05$). In addition, the differences between landing on the flat and slant surfaces were examined using a 2 × 2 (brace × surface) repeated measures ANOVA. The results showed that the slant surface landing resulted in significantly earlier maximum inversion angle occurrence. Significantly higher maximum eversion and inversion velocities were also found in the slant surface landing compared to the inversion drop test. In the comparison of landing on the slant surface and flat surfaces, the results showed that slant surface landing led to smaller 1st and 2nd peak vertical and horizontal GRFs, greater maximum inversion and its range of motion (ROM), and smaller dorsiflexion ROM. The results suggest that the slant surface landing simulate ankle sprain mechanism better than the inversion drop test. Subjects adopted a softer landing strategy when landing onto the flat surface and a stiffer strategy when landing onto the slant surface.

INTRODUCTION

The ankle is one of the most traumatized body sites in sports and injuries to this joint account for 10 - 30% of all sports injuries [15]. The most recent NCAA injury data over 16 years (1988 – 2004) showed that ankle ligament injuries have the highest injury rate at 14.9% of all reported injuries in 15 sports, ranging from 2.8% in women's ice hockey to 26.6% men's basketball [19]. Of those ankle injuries, the most common ankle injury is the lateral ankle sprain, which is caused by excessive inversion of a plantarflexed ankle [23].

It has become a norm to use an ankle brace in the prevention, and rehabilitation of ankle sprains. Research investigating the restricting effects of ankle braces has typically utilized a rapidly induced inversion drop test using an ankle inversion platform commonly referred as a trapdoor [1, 2, 6-8, 13, 14, 37], and rarely by a drop landing on a flat [18] or slant surface [26, 45]. In the findings of inversion drop (trapdoor) studies, ankle ROM in plantarflexion/dorsiflexion is significantly reduced with the application of an ankle brace [13]. Maximum inversion angle after touchdown and maximum and mean inversion velocities are reduced when wearing an ankle brace [2, 6, 7, 14 48]. Ankle braces were also shown to protect the ankle during the free fall phase of the inversion drop test without bodyweight loading, therefore causing decreased maximum inversion angle at the loading phase after contact [2, 14]. One common conclusion from ankle brace studies is that a semi-rigid design restricts ankle ROM most effectively during ankle inversion movement, with minimum adverse effects on athletic performance in jump, rebound, and agility tests [17, 30, 31].

The inversion drop device is limited to inducing only the inversion at the ankle. However, a lateral ankle sprain is caused by a combination of ankle inversion and plantar flexion. Most lateral ankle sprains occur in landing on an uneven surface from a jump. During landing, the ankle joint is naturally placed into a plantarflexed and inverted position prior to touchdown. Greater impact loading is applied to the body and the ankle joint during landing, and therefore greater inversion loading is applied to the ankle joint compared to the inversion drop movement on an inversion drop device. A landing onto a slanted surface would create a more realistic simulation of an ankle inversion sprain, and may provide more realistic results compared to the trapdoor testing condition [45]. In contrast to ankle brace studies using an inversion drop testing protocol, a very limited number of studies employed drop landing in their experimental protocol [18, 26, 44, 45]. Among these, only one study actually employed landing testing protocol on a slant surface [45]. Venesky found a greater ankle eversion torque, and knee external rotation torque while wearing an ankle brace during drop landing on a slant (inversion slope) surface of 20° [45]. This angle is smaller than the common inversion angle of 30° used in most inversion drop studies. McCaw et al. examined soft and stiff drop landings and found a significantly reduced maximum ankle dorsiflexion velocity while wearing an ankle brace [26]. Hodgson and colleagues found that the peak vertical ground reaction force and loading rate at toe contact significantly increased and the ankle dorsiflexion angle at toe contact significantly decreased during the drop landing onto a flat surface wearing an ankle brace [18]. Different from those studies, Ubell and colleagues found that participants wearing semi-rigid braces had significantly greater success rates in keeping balance for three seconds after the one foot landing with a 24° inversion fulcrum affixed to the heel of the shoes, compared to the lace-up brace and no brace conditions [44].

Therefore, the purpose of this study was to investigate kinematic differences between two ankle brace testing protocols, drop landing on a slanted surface and inversion drop test on a trapdoor device. Differences in kinematics and ground reaction forces of the drop landing wearing an ankle brace on flat and lateral slant surfaces were also investigated.

MATERIALS AND METHODS

Participants: A total of 11 healthy subjects (age: 24.6 ± 3.5 years, height: 1.70 ± 0.10 m, mass: 65.6 ± 14.9 kg), 6 females and 5 males, from the University of Tennessee, Knoxville and the surrounding areas were recruited to participate in this study. 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. Subjects signed the informed consent form approved by the Institutional Review Board at The University of Tennessee, Knoxville.

Instrumentation: A 7-camera motion analysis system (240 Hz, Vicon *PEAK* Motion Analysis Inc., Oxford, UK) was used to obtain the three-dimensional (3D) kinematics during data collection, with reflective anatomical and tracking markers placed on both sides of the foot, ankle, and leg, knee, thigh and pelvis during testing. Two force platforms (1200 Hz, American Mechanical Technology Inc., Watertown, MA, USA) were used to measure the ground reaction forces (GRF) and the moments of forces simultaneously with the 3D kinematics in the drop landing movement.

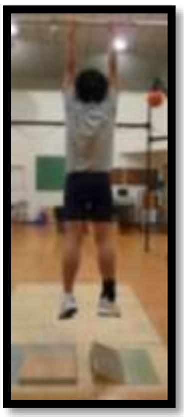
A slant surface (45.72 cm (L) × 22.86 cm (W) × 11.43 cm (H)) with a 25° slope was constructed and mounted the right side force platforms with double sided tape (Figure 1a). Strips of sand paper were adhered to the surface to ensure proper landing without slipping (Figure 1a). It was used in landing conditions to induce 25° inversion to the ankle after touchdown from a drop landing. The 25° inversion slope was chosen to maximize ankle inversion without placing the ankle in an injurious position after extensive piloting testing. A flat surface (40 cm (L) × 40 cm (W) × 4 cm (H)) wooden board was mounted on the top of the left force platform to provide support for the left leg in order to avoid imbalance after drop landing (Figure 1a).

An adjustable overhead bar controlled by an electrical hoist was hung from the ceiling at a height 0.45 m above the center of the slant surface measured from the mid-heel of the participant's right foot (Figure 1b). The subject was instructed to hold the bar with both hands at shoulder width and release hands to land with the right foot on the slant surface and the left foot on the left force platform.

A customized inversion drop trapdoor platform (91.5 cm (L) x 46 cm (W) x 20 cm (H)) was used in an inversion drop test to attempt to invert the ankle to 25º during testing conditions (Figure 1c). In general, 30° is the most common tilting angle used [1, 5, 8, 9, 24, 44]. However, the inversion angle in this study was chosen to match the inversion angle of the slant surface employed during drop landing tests. The inversion surface was released through a pneumatically controlled switch.

A semi-rigid ankle brace with a heel strapping system (Element, DeRoyal Industries, Inc, TN) was used on the right side of the participant during testing (Figure 2). A pair of standard lab running shoes was worn during testing conditions. The same investigator applied all of the braces to the participants during the test sessions according to manufacturer's instruction.

a)



b)

c)

Figure 1.The testing conditions: a) slant surface, b) drop landing onto slant surface, c) inversion drop test.

Figure 2.The Element Ankle Brace.

Experimental Protocol: The participant began the test session with a standard warm-up using a treadmill for 4 minutes and stretching. After the warm-up, the ankle width with and without the ankle brace was measured using a caliper (Anthropometer, Model 01291, Lafayette instrument company, Lafayette, Indiana). The measurements were repeated 3 times by the same investigator for all participants.

During dynamic testing session, the participant performed five trials in each of six dynamic movement conditions: an ankle inversion drop test on the inversion platform without brace (ID_NB) and with brace (ID_BR), drop landing from 0.45 m on to slant surface without brace (LS_NB) and with brace (LS_BR), and drop landing from 0.45 m on to flat surface without brace (LF_NB) and with brace (LF_BR). During the inversion drop test, the subject stood upright on the platform with bodyweight distributed evenly between the two feet with the arms kept in front of the body. The inversion drop was initiated by the data collector through a pneumatically controlled switch when subject was ready after standing on the platform without prior knowledge of the subject. A successful trial was a trial where the subject was able to keep balance after dropping with the right foot inverted. During the drop landing onto the slant surface

(Figure 1b), the subject landed bilaterally with the right foot on the center of the slant surface and left foot on the left force platform. The participant was given ample time to become familiar and practice the testing movements on the trapdoor and drop landing prior to the actual testing. A successful trial was a trial where the subject landed without losing balance in any direction. The order of brace conditions (with or without brace) was first randomized, and the testing movements (inversion drop, drop landing on slant surface and flat surface) were then randomized within each brace condition.

Data and Statistical Analysis Procedures: Visual3D (C-Motion, Inc., Germantown, MD, USA) 3D biomechanical analysis suite was used to compute 3D kinematic variables for the right lower extremity. A customized computer program (MS VisualBasic 6.0) was used to determine critical events and values of the computed variables from outputs of Visual3D. The inversion drop test was analyzed from the contact of the trapdoor surface to the ground to 500 ms after the contact. The drop landing movement was analyzed from the foot contact to the maximum knee flexion. The 3D angular kinematics were computed using a Cardan sequence (X-Y-Z) and a right-hand rule. For the drop landing movement, ground reaction forces were normalized to bodyweight (BW).

In order to examine effects of bracing on differences between the inversion drop and landing on the slant surface, a 2 × 2 (brace × movement) repeated measures analysis of variance (ANOVA) was used to evaluate selected variables, with an alpha level of 0.05 (SPSS 15.0, SPSS Inc., Chicago, IL). In addition, surface effects during landing on the flat and slant surfaces were examined using a 2 × 2 (brace × surface) repeated measures ANOVA.

RESULTS

Comparison between landing on slant surface and inversion drop test

The results of the frontal plane kinematics showed that the contact inversion angle significantly decreased after wearing the ankle brace for both slant surface landing and inversion drop conditions ($F = 6.93$, $p = 0.025$, Table 1). There was a significant brace × movement interaction for the maximum inversion angle (Figure 3a and Table 1). The brace caused more significant reduction of the maximum inversion angle in the inversion drop conditions than the slant surface landing conditions ($F = 9.33$, $p = 0.014$). Without the brace, the maximum inversion angle increased from slant surface landing to inversion drop condition, however this angle decreased while wearing the ankle brace. The time to the peak inversion angle for the slant surface landing occurred significantly sooner than the inversion drop on the trapdoor ($F = 277.5$, $p < 0.05$, Table 1). The brace did not cause any significant change in the range of motion (ROM) in both slant surface landing and inversion drop conditions. Both testing conditions showed an inversion range of motion (Figure 4a and 4b). The minimum inversion angle was found only in the inversion drop condition. However, no significant differences were found for this variable.

For the angular velocity, the inversion drop condition showed a contact eversion velocity which was significantly reduced after wearing the brace while the slant surface landing had contact inversion velocity which was significantly increased after wearing the brace (Table 2). The brace caused significant decrease in the peak eversion velocity in the slant surface landing and inversion drop conditions ($F = 7.45$, $p = 0.021$). A significant brace × movement interaction was also found for this peak eversion velocity in the slant surface landing and inversion drop conditions ($F = 10.35$, $p = 0.009$, Figure 5a). The brace caused huge decrease in the peak eversion velocity for the inversion drop condition, however this brace effect was minimized in the slant surface landing condition (Table 2). The time to the peak eversion velocity occurred significantly sooner in the braced slant surface landing condition ($F = 44.28$, $p < 0.05$, Table 2). This time occurred significantly sooner in the inversion drop condition ($F = 78.54$, $p < 0.05$) when compared to the slant surface landing condition. For the peak inversion velocity, a significant brace × movement interaction was found in the slant surface landing and inversion drop conditions ($F = 23.57$, $p = 0.001$, Figure 3b and Table 2). Further examination suggested that the peak inversion velocity increased from the no brace to the brace condition in the slant surface landing conditions whereas it decreased in the inversion drop condition. In addition, a significantly smaller peak inversion velocity was found in the inversion drop condition compared to the slant surface landing ($F = 23.57$, $p = 0.001$, Table 2). There was a significant brace × movement interaction for the time to the peak inversion velocity in the slant surface landing and inversion drop conditions ($F = 8.20$, $p = 0.017$, Figure 3c and Table 2). In the slant surface landing condition, the time to the peak inversion velocity occurred significantly earlier for the braced landing, however this time significantly delayed in the inversion drop conditions while wearing the brace ($F = 5.88$, $p = 0.036$). The time to the peak inversion velocity occurred significantly earlier for the slant surface landing condition compared to the inversion drop condition ($F = 109.4$, $p < 0.05$, Table 2).

The results of the sagittal plane kinematics showed that the contact angle and dorsiflexion ROM ($p < 0.05$) were significantly reduced after wearing the ankle brace (Table 3). The landing on the slant surface had significantly greater dorsiflexion ROM compared to the inversion drop condition ($F = 92.58$, $p < 0.05$). For the angular velocity, the ankle brace significantly decreased the contact velocity and maximum dorsiflexion velocity in the slant landing ($F = 33.59$, $p < 0.05$) condition as well as the inversion drop conditions ($F = 146.2$, $p < 0.05$, Table 3). But for the inversion drop condition, the contact dorsiflexion velocity increased from no brace to brace condition. In addition, significant reductions of the contact dorsiflexion velocity and maximum dorsiflexion velocity were found from slant surface landings to the inversion drop conditions ($p < 0.05$). A significant brace × movement interaction of time to the maximum dorsiflexion velocity was found between the slant surface landing and inversion drop conditions ($F = 5.32$, $p = 0.044$, Table 3). In the slant surface landing, the maximum dorsiflexion velocity

Table 1. Average frontal plane ankle angle variables: mean ± STD

Cond	Angle					
	Cont_Inv (deg)	Max_Inv* (deg)	TMax_Inv (s)	ROM (deg)	Max_Ev (deg)	TMax_Ev (s)
LF_NB	5.6±3.4 [a,b]	5.2±3.9 [b]	0.042±0.039	-6.71±3.1 [b]	-1.33±4.4	0.132±0.042
LF_BR	2.2±2.3	1.8±4.8	0.084±0.104	-4.04±3.1	-1.8±4.2	0.130±0.057
LS_NB	11.8±3.2 [1]	25.2±3.9 [1]	0.060±0.011 [2]	13.5±5.1	--	--
LS_BR	8.4±3.2	22.6±5.2	0.055±0.010	14.4±4.7	--	--
ID_NB	12.3±4.4	27.7±6.1	0.239±0.046	13.8±3.5	10.2±4.0	0.062±0.040
ID_BR	6.6±4.1	22.0±4.8	0.241±0.050	14.8±3.5	5.0±5.1	0.055±0.025

Note: Cont_Inv: inversion contact angle, Max_Inv: maximum inversion angle, TMax_Inv: time to the maximum inversion angle, Max_Ev: masimum eversion angle, TMax_Ev: time to the maximum eversion angle, ROM: range of motion during landing.

[a]: significantly different between NB and BR in landing conditions ($p<0.05$)

[b]: significantly different between Flat and Slant surfaces in landing conditions ($p<0.05$)

[1]: significantly different between NB and BR in slant surface and inversion drop conditions ($p<0.05$)

[2]: significantly different between slant surface landing and inversion drop conditions ($p<0.05$)

[*]: significant brace × movement interaction in the slant surface landing and inversion drop ($p<0.05$), "--": not available or of no interests.

Table 2. Average frontal plane ankle velocity variables: mean ± STD

Cond	Velocity				
	Cont_V (deg/s)	Max_Ev_V [#, *] (deg/s)	TMax_Ev_V (s)	Max_Inv_V [*] (deg/s)	TMax_Inv_V [*] (s)
LF_NB	-127.1±82.8 [a,b]	-232.3±78.0 [a,b]	0.041±0.019 [a,b]	--	--
LF_BR	-55.6±55.8	-119.7±39.3	0.039±0.017	--	--
LS_NB	163.9±128.0 [1,2]	-129.9±47.4 [1,2]	0.081±0.013 [2]	273.8±156.0 [2]	0.027±0.009 [1,2]
LS_BR	256.7±119.7	-115.9±46.9	0.070±0.013	373.1±121.1	0.021±0.007
ID_NB	-26.8±78.6	-125.0±65.6	0.030±0.014	166.5±67.9	0.173±0.060
ID_BR	-17.2±50.6	-54.9±29.3	0.037±0.022	69.1±59.7	0.245±0.085

Note: Cont_V: contact angular velocity, Max_EV_V: maximum eversion angular velocity
TMax_Ev_V: time to the maximum eversion angular velocity, Max_Inv_V: maximum inversion angular velocity
TMax_Inv_V: time to the maximum inversion angular velocity
[a]: significantly different between NB and BR in landing conditions ($p<0.05$)
[b]: significantly different between Flat and Slant surfaces in landing conditions ($p<0.05$)
[1]: significantly different between NB and BR in slant surface and inversion drop conditions ($p<0.05$)
[2]: significantly different between slant surface landing and inversion drop conditions ($p<0.05$)
[#]: significant brace × surface interaction in landing conditions ($p<0.05$), [*]: significant brace × movement interaction in the slant surface landing and inversion drop ($p<0.05$), “--”: not available or of no interests.

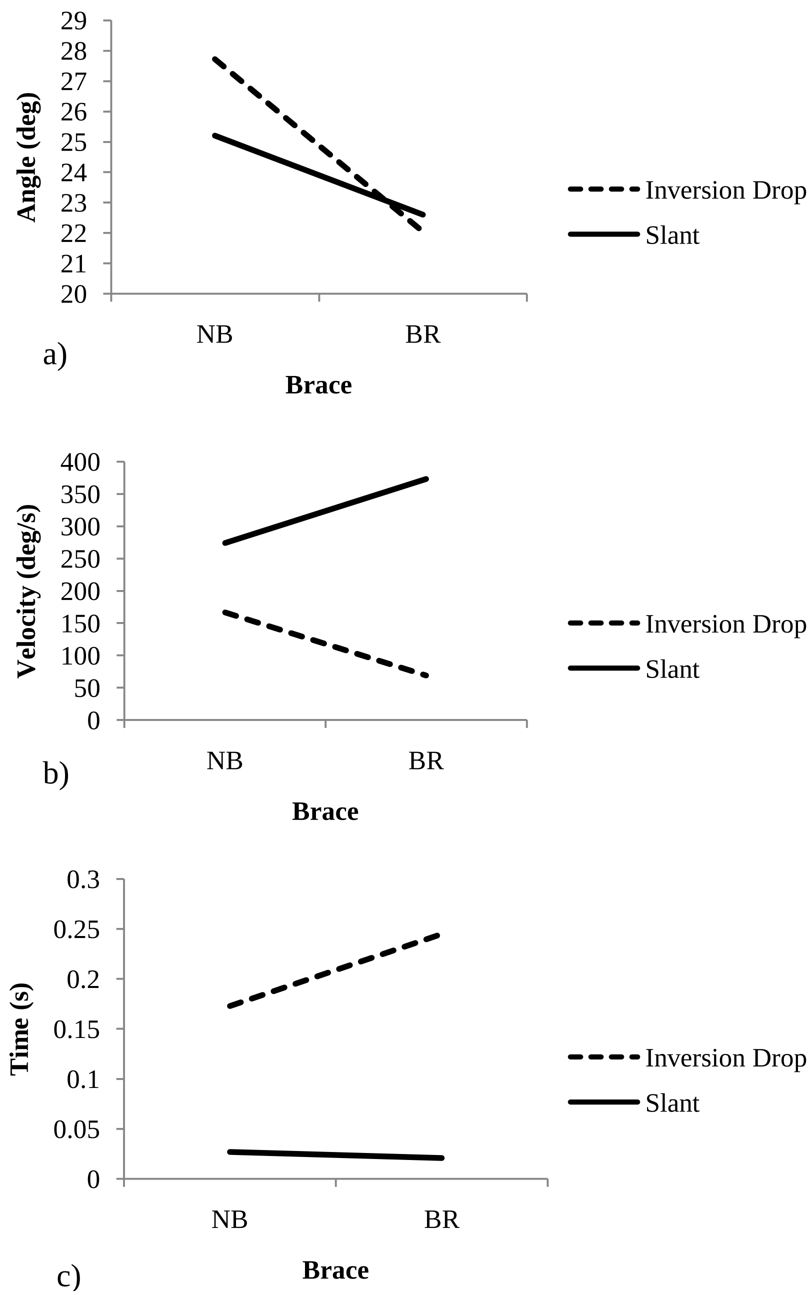
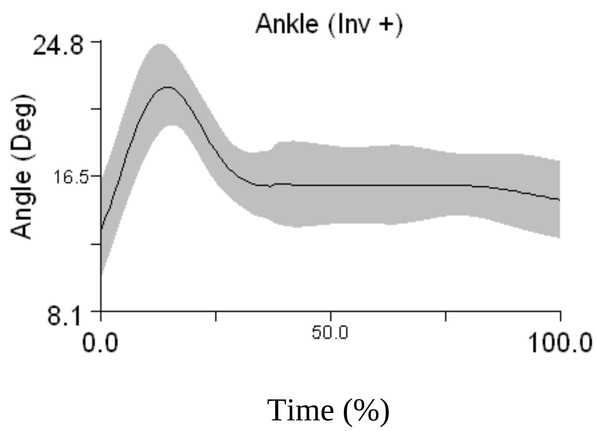
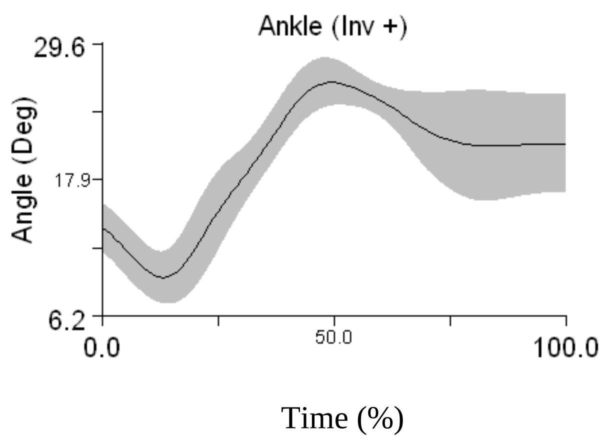


Figure 3. Significant interactions for ($p < 0.05$) a) the maximum inversion angle (Max_Inv), b) the maximum inversion velocity (Max_Inv_V), and c) the time to the maximum inversion velocity (TMax_Inv_V) .



a)



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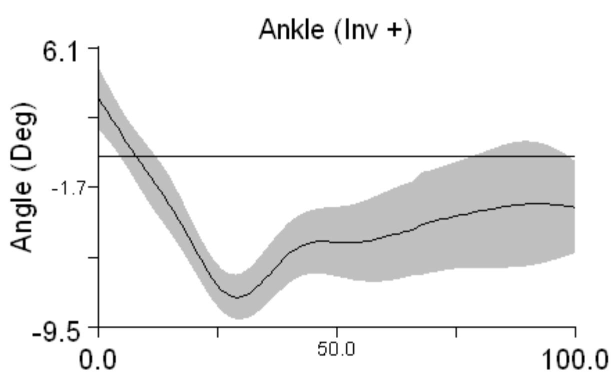
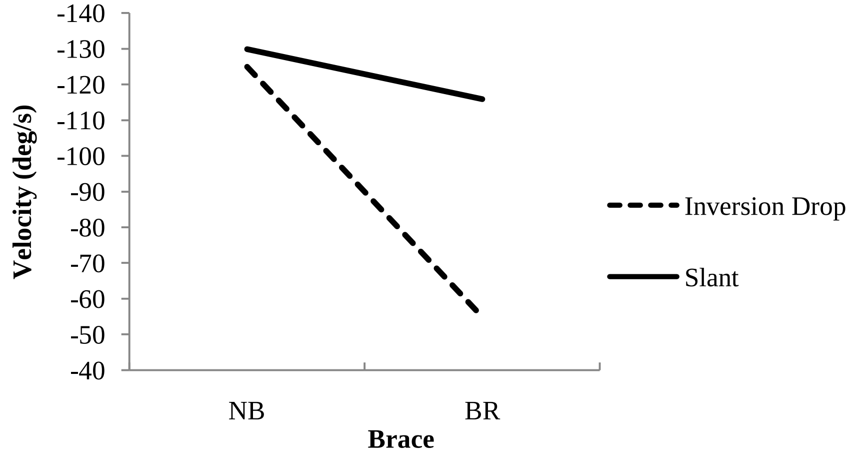
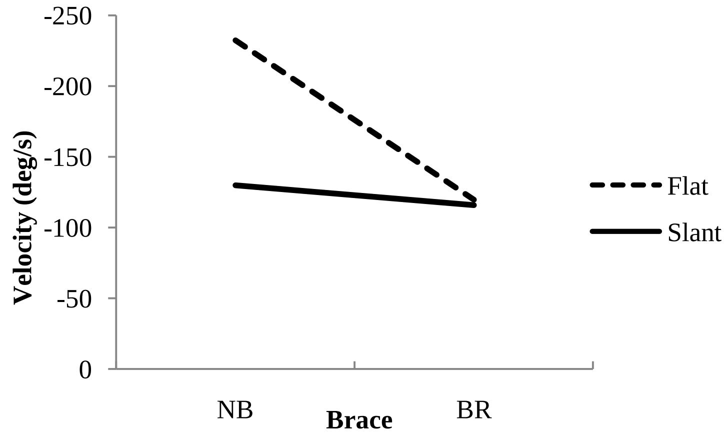


c)

Figure 4. Representative ensemble frontal plane ankle angle curves during: a) landing on slant surface, b) inversion drop, c) landing on flat surface.



a)



b)

Figure 5. Significant interactions ($p<0.05$) for a) maximum eversion velocity (Max_Ev_V) in the slant surface landing and inversion drop conditions, b) the maximum eversion velocity (Max_Ev_V) in the two landing conditions.

occurred about at the same time with brace and without the brace, however in inversion drop condition, this time occurred significantly earlier wearing no brace compared to wearing the brace (F = 5.41, p = 0.042). Additionally, the time to the maximum dorsiflexion velocity was significantly delayed for the inversion drop condition compared to the slant surface landing condition (F = 18.47, p = 0.002, Table 3).

Table 3. Average sagittal plane ankle kinematic variables: mean ± STD

Cond	Cont_PF (deg)	ROM_DF (deg)	Cont_DF_V (deg/s)	Max_DF_V (deg/s)	TMax_DF_V [*] (s)
LF_NB	-18.5±8.7 [a]	44.4±7.9 [a,b]	500.5±77.8 [a,b]	788.4±138.1 [a,b]	0.023±0.004 [b]
LF_BR	-7.1±6.0	35.2±5.1	451.5±82.0	643.7±108.9	0.022±0.004
LS_NB	-17.9±9.2 [1]	35.3±5.1 [1,2]	393.9±90.5 [2]	662.2±140.5 [1,2]	0.026±0.003 [1,2]
LS_BR	-5.0±8.7	28.1±6.2	306.9±110.3	504.5±144.4	0.026±0.002
ID_NB	-19.6±5.6	16.7±5.2	25.7±69.0	195.8±66.7	0.036±0.013
ID_BR	-4.4±6.3	6.2±5.2	34.0±28.5	97.5±54.9	0.072±0.046

Note: Cont_PF: plantar-flex contact angle, ROM_DF: dorsi-flex range of motion, Cont_DF_V: dorsi-flex contact angular velocity
Max_DF_V: maximum dorsi-flex angular velocity, TMax_DF_V: time to the maximum dorsi-flex angular velocity
[a]: significantly different between NB and BR in landing conditions (p<0.05)
[b]: significantly different between Flat and Slant surfaces in landing conditions (p<0.05)
[1]: significantly different between NB and BR in slant surface and inversion drop conditions (p<0.05)
[2]: significantly different between slant surface landing and inversion drop conditions (p<0.05)
[*]: significant brace × movement interaction (p<0.05)

Comparison between landing on flat surface and slant surface

The statistical results of the landing activities showed a significantly higher 1st peak vertical GRF in flat surface landing (Figure 6a and 6b) compared to the slant surface landing (Figure 6c and 6d) ($F = 26.74$, $p = 0.004$). In addition, the 2nd peak GRF was significantly smaller in the slant surface landing compared to the flat surface landings ($F = 15.25$, $p = 0.004$, Table 4). A significant delayed time to the 2nd peak vertical GRF wearing the ankle brace in both landing conditions was also found. There was a significant brace × surface interaction for the first peak lateral GRF ($F = 17.17$) (Figure 7 and Table 4). The brace caused higher 1st peak lateral GRF in the flat surface landing whereas it caused a decrease of it in the landing on the slant surface (Figure 6). Furthermore, the slant surface caused a significant decrease in the first ($F = 17.17$, $p<0.05$) and second peak lateral GRFs ($F = 7.99$, $p = 0.018$, Table 4).

The results of the frontal plane kinematics showed that the contact inversion angle significantly decreased after wearing the ankle brace for both flat and slant surface landing conditions ($F = 8.62$, $p = 0.015$, Table 1). Landing on the slant surface caused significant higher contact inversion angle compared to the flat surface landing ($F = 136.7$, $p < 0.05$). The maximum inversion angle was significantly increased from the flat surface landing to the slant surface landing conditions ($F = 368.4$, $p < 0.05$, Table 1). The brace did not cause any significant change in the range of motion (ROM) in both flat and slant surface landing conditions. The only difference was that flat surface landing condition showed an eversion range of motion while slant surface landing showed an inversion range of motion ($F = 215.5$, $p < 0.05$, Figure 4a and 4c). The maximum eversion angle was found only in the flat surface landing. However, no significant differences were found for this variable.

Table 4. Average peak GRF variables: mean ± STD

Cond	F1_Z (BW)	TF1_Z (s)	F2_Z (BW)	TF2_Z (s)	FMin1_X [#] (BW)	TFMin1_X (s)	FMin2_X (BW)	TFMin2_X (s)	TOff (s)
LF_NB	1.28±0.25 [b]	0.011±0.002 [b]	3.20±0.64 [b]	0.049±0.011 [a]	-0.23±0.06 [b]	0.017±0.009	-0.31±0.08 [b]	0.053±0.023	0.224±0.072
LF_BR	1.32±0.25	0.009±0.002	3.38±0.73	0.040±0.008	-0.26±0.08	0.021±0.014	-0.28±0.08	0.069±0.046	0.209±0.078
LS_NB	0.95±0.22	0.012±0.002	2.86±0.55	0.046±0.010	-0.09±0.06	0.026±0.013	-0.21±0.07	0.065±0.024	0.199±0.070
LS_BR	0.85±0.25	0.011±0.003	2.69±0.56	0.041±0.008	-0.02±0.07	0.020±0.009	-0.23±0.11	0.058±0.016	0.202±0.059

Note: F1_Z: 1st peak vertical GRF, TF1_Z: time to the 1st peak vertical GRF, F2_Z: 2nd peak vertical GRF, TF2_Z: time to the 2nd peak vertical GRF
FMin1_X: 1st peak medial GRF, TFMin1_X: time to the 1st peak medial GRF, FMin2_X: 2nd peak medial GRF,
TFMin2_X: time to the 2nd peak medial GRF, TOFF: the time of maximum knee flexion from touchdown.
[a]: significantly different between NB and BR in landing conditions ($p<0.05$)
[b]: significantly different between Flat and Slant surfaces in landing conditions ($p<0.05$)
[#]: significant brace × surface interaction in landing conditions ($p<0.05$)

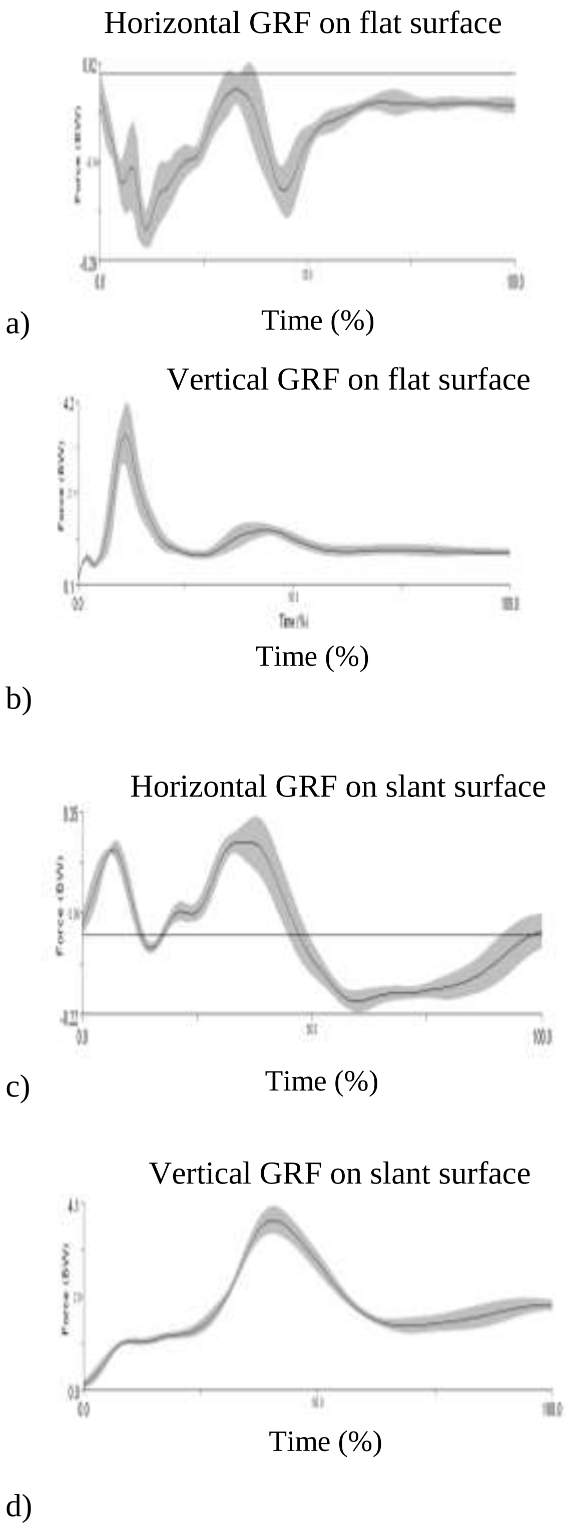


Figure 6. Representative ensemble horizontal and vertical GRF curves during: a) and b) landing on flat surface, c) and d) landing on slant surface.

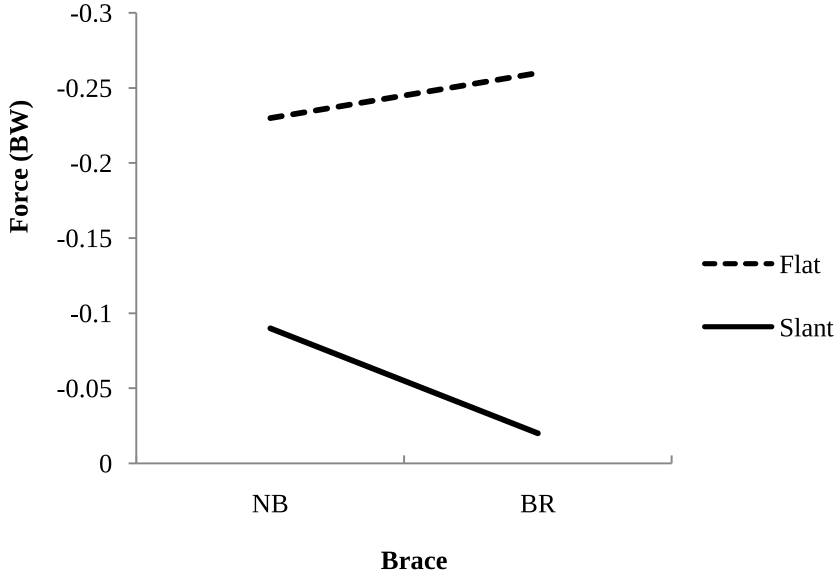


Figure 7. Significant interactions ($p<0.05$) for the1st peak horizontal GRF (FMin1_X) in landing conditions.

For the angular velocity, the flat surface landing condition showed a contact eversion velocity which was significantly reduced after wearing the brace while the slant surface landing had contact inversion velocity which was significantly increased after wearing the brace (Table 2). The brace caused significant decrease in the peak eversion velocity in all landing conditions ($F = 13.97$, $p = 0.004$, Table 2). The slant surface landing conditions showed significantly smaller peak eversion velocity compared to the flat surface landing ($F = 12.15$, $p = 0.006$) and this difference was mainly found in the no brace conditions shown in the significant brace × surface interaction ($F= 22.09$, $p = 0.001$, Figure 5b). The time to the peak eversion velocity occurred significantly sooner in the braced landing conditions ($F = 44.28$, $p < 0.05$, Table 2). Compared to the slant surface landing condition this time occurred significantly sooner in the flat surface landing condition ($F = 44.28$, $p < 0.05$). No peak inversion velocity and the time to this velocity were found in the flat surface landing condition, in the slant surface landing condition, the time to the peak inversion velocity occurred significantly earlier for the braced landing (Table 2).

The results of the sagittal plane kinematics showed that the contact angle and dorsiflexion ROM ($p< 0.05$) were significantly reduced after wearing the ankle brace (Table 3). The landing on the flat surface had significantly greater dorsiflexion ROM ($F = 27.89$, $p < 0.05$) compared to the landing on the slant surface. For the angular velocity, the ankle brace significantly decreased the contact velocity and maximum dorsiflexion velocity in the flat ($F = 11.45$, $p = 0.007$) and slant landing ($F = 33.59$, $p < 0.05$) conditions (Table 3). In addition, significant reductions of the contact dorsiflexion velocity and maximum dorsiflexion velocity were found from the flat surface to the slant surface landings conditions ($p < 0.05$). The time to the maximum dorsiflexion velocity occurred significantly sooner in the flat surface landing than the slant surface landing (F = 9.59, p = 0.011, Table 3).

DISCUSSION

Comparison between landing on slant surface and inversion drop test

The main purpose of the study was to investigate kinematic difference of two ankle brace testing protocols, drop landing on a slant surface and inversion drop, in restriction of ankle inversion motion. The results from the current study showed that there was no significant difference for the contact angle (inversion) and maximum inversion angles between slant surface landing and inversion drop conditions. These data seem to suggest that these two testing protocols are similar in yielding frontal plane ankle kinematics. However, further examination of the frontal plane kinematic data indicated that there were unique characteristics of ankle frontal plane angles and other related variables in those two testing conditions. The ensemble ankle angle curves in the frontal plane showed a small inversion and large eversion in early contact during slant surface condition whereas the inversion drop shows an initial small eversion and large inversion for the landing phase. More importantly, the peak inversion occurred at different times under the two conditions . The peak inversion for the landing on the slant surface occurred at about 58 ms which is much earlier than the 240 ms for the inversion drop. In addition, the peak inversion velocities were significantly higher at 323 deg/s and occurred significantly earlier at 0.024 s in the slant surface landing compared to the 118 deg/s and 0.209 s for the peak inversion velocity and its time, respectively in the inversion drop. Based upon previous study about the muscle activation system during acute ankle sprain, 120 ms is the minimum time to generate a protective muscular response [22]. During the inversion drop of the current study, the maximum inversion angle was attained around an average of 240 ms after the initiation of platform drop and the ankle evertors may have time to respond and provide protection against sudden inversion. Ricard et all. reported that a peak inversion of 35.3° was attained 117 ms after the inversion drop initiation while testing ankle inversion drop on a 35° tilting angle [33]. In our study, we used 25° inversion angle which reduced the contact and maximum inversion angles and velocities, and delayed the occurrence of the maximum inversion velocity compared to more realistic ankle sprain situations.

On the other hand, the maximum inversion angle was attained around an average of 58 ms for the slant surface landing in our study which suggest that the ankle evertors do not have enough time to respond and provide protection to the inversion perturbation. The inversion drop test only allows the human body to drop from a limited height whereas the drop landing allows the body to land from a higher height in the most actual ankle sprain situations and introduce greater inversion loading. We choose 25° inversion angle for both testing protocols of landing on the slant surface and inversion drop for the purposes of safety and equitable comparisons. The landing from 45 cm on a 25° inversion sloped surface induced contact and peak inversion velocities of 163.9 °/s and 273.8 °/s for the slant surface landing, and -26.8 °/s and 166.5°/s for the inversion drop condition, respectively without brace. In actual ankle sprains during landing, the inversion angle would be greater and would introduce greater loading with higher peak inversion angle and inversion velocity which would occur at an earlier time. The angular velocity that an ankle experiences during an ankle sprain may also contribute to the severity of the injury [25]. These results further suggest that the slant surface landing protocol provides a better and more realistic testing protocol to simulate acute ankle sprain mechanisms than the inversion drop test.

To our surprise, there is no significant difference for the contact plantar flexion angle between slant surface landing and inversion drop conditions. Initially we hypothesized that slant surface landing would induce greater contact plantarflexion angle therefore proving this testing method to be more realistic than the inversion drop, since majority of ankle sprains occur when ankle is placed into a combination of inversion and plantarflexion. The tilting platforms used by most previous stuides allowed participants to drop primarily into inversion without sagittal-plane plantarflexion motion [1, 2, 6-8, 13, 14, 37]. To our knowledge, only two studies have the combined plantarflexion and inversion in the design of the inversion drop platforms [20, 25]. No studies have been conducted using a drop landing protocol on a surface with a combination of plantarflexion and inversion. It would be interesting to examine the effects of such a testing protocol on GRF and ankle kinematics in future.

Ankle sprains are often reported during landing from a jump in sports. The vertical GRF ranges from 2.3 to 7.1 times body weight when landing from a vertical jump [43]. The peak vertical GRFs in our study were 3.2 and 2.7 BW for the flat and slant surface, respectively. One of the reasons that these peaks were small is that subjects in our study landed with one foot on the force platform and the GRFs were normalized to the entire body weight. As a consequence of this normalization, it actually reduced the peak GRFs by almost 100% compared to some of peak GRF data reported in the literature. Although, there has been no data on GRFs for the inversion drop condition, it can be assumed that inversion drop condition would induce less peak vertical GRF than the drop landing conditions did. The increased dorsiflexion ROM during the slant surface landing condition indicated greater energy absorption at the ankle joint, compared to the inversion drop condition.

With the application of the ankle brace, the inversion contact angle and maximum inversion angles were reduced significantly in both testing protocols. The changes from the no brace to the brace condition were characterized by reductions of 3.4° and 2.6° in the slant surface landing and reductions of 5.7° and 5.7° in the inversion drop condition, for the contact angle and maximum inversion angle respectively. However, the application of the ankle brace did not reduce the contact and maximum inversion velocities as we expected during the slant surface landing. In fact, both variables increased significantly during the landing condition. These landing results are somewhat counter-intuitive and warrant further investigation. They may present adverse effects on ankle joints. However, the ankle brace in the inversion drop did reduce the contact and peak inversion velocities significantly. These results in the inversion drop are supported by previous findings [2, 14, 18, 32, 36]. In addition, the ankle brace significantly reduced the contact and dorsiflexion ROM, and peak dorsiflexion velocity and its time in slant surface landing and inversion drop conditions. The results from the current study are supported by the previous findings by Zhang et al. [48] and provided additional evidence for the protective effects of ankle brace in preventing ankle sprains.

Comparison between landing on flat surface and slant surface

The second purpose of the study was to investigate effects of ankle brace on angular kinematics and ground reaction forces in drop landing with different lateral surface inclinations. During the flat surface landing, the greater first and second peak vertical and lateral GRFs were observed compared to the slant surface landing. These increased peak GRFs are associated with increased sagittal and frontal kinematics. We initially speculated, on the basis of the VGRF data, the higher 1st peak vertical GRF in the flat surface landing may be due to the fact that subjects performed a toe-heel landing strategy at touchdown. A closer examination of sagittal kinematic results showed that subjects initially exhibited similar contact plantarflexion angles in both landing conditions. Surface difference did not affect the ankle position during contact and therefore no significant difference in the touchdown technique was observed in both landing conditions. However, significantly greater dorsiflexion ROM , contact and maximal dorsiflexion velocities, and shorter time to maximum dorsiflexion velocity were observed in the flat surface landing condition compared to the slant surface landing (Table 3). This may imply a softer landing style with more knee flexion during flat surface landing compared to the slant surface landing. It was suggested that during normal drop landing (onto flat surface), the body does not maximize the energy absorption capacity of ankle plantarflexors compared to stiff landing (extended knee) which requires greater ankle plantarflexor contraction to aid energy absorption [38]. In the landings on the slant surface, the movement of the ankle joint is constrained by the laterally sloped surface resulting in the reduced ROM and peak dorsiflexion velocity in sagittal plane and therefore the reduced peak GRFs. The amount of energy absorption is normally related to the amount of ROM in the joints [10, 27, 49]. Future investigation of the knee and hip joints may provide better picture of the landing techniques.

The results of this study suggest that subjects adopted a softer landing strategy when landing onto the flat surface and a stiffer strategy when landing onto the slant surface. The stiff strategy was reflected in the reduced contact dorsiflexion, dorsiflexion ROM, and maximum dorsiflexion velocities. These kinematic changes indicate the need for the subjects to co-contract ankle joint muscles to stabilize the ankle joint and avoid injury in the unstable (slant surface) landing condition. Although the sagittal plane ankle kinematics is significantly changed in the slant surface landing, the frontal plane ankle kinematics were modified even more to adapt to the changed surface condition. As the slant surface imposes an inversion perturbation, it eliminates eversion motion that is observed in the normal landing on the flat surface. Since the eversion motion at the subtalar joint is commonly involved in impact attenuation during gait and landing movements, the lateral ankle ligaments and evertors play a major role in resisting the inversion during the landing condition. Landing on the slant surface led to the reduced 1^{st} and 2^{nd} peak vertical as well as horizontal 1^{st} and 2^{nd} GRFs, partially due to the fact that the foot contact is less perpendicular to the landing surface. Hodgson also did not find any significant increase of the 2^{nd} peak vertical GRF (associated with heel contact) during flat surface landing with brace [18]. The changes of the peak horizontal GRF in slant surface landing from the regular landing showed an opposite trend of what we expected. We expected to see an increase in the horizontal GRF due to the increased landing surface slope. The frontal plane kinematic results showed that the reduced lateral GRF are related to significant changes in the frontal kinematics. Compared to the flat surface landing, individuals landing on the slant surface showed a mean of 6.2° more contact inversion angle and 20° more peak inversion compared to the flat surface landing. In addition, an inversion contact velocity was observed in the slant surface landing condition compared to the eversion contact velocity seen in the normal landing. Landing on the slant surface might have introduced several additional factors that could influence the magnitudes of lateral (and vertical) peak GRFs. Landing on the slant surface requires greater friction between the shoe and surface to avoid slip. To avoid this, we actually placed sand paper on the slant surface during the testing. The increased friction during the landing phase may cause a greater energy dissipation therefore reduced peak GRFs. Furthermore, the more inverted contact ankle angle places the lateral ankle ligament complex under a tighter and stretched state thus allowing this ligament complex to contribute more to impact attenuation, which further contribute to the reduced GRFs. The flat surface landing enabled the individuals to make foot contact more perpendicular to the landing surface, the ankle is in eversion movement during the early part of the landing phase in the normal landing condition. As discussed earlier, a lack of eversion motion in the ankle joint was observed in the ankle joint during slant surface landing, which is not only related to the foot and ankle position at the ground contact but also related to the elimination of eversion ROM after the ground contact. To avoid injury to the lateral ligaments due to further inversion and maintain balanced ankle position during the landing, the subjects might have exerted a greater eversion moment through the ankle evertors. Further investigation on the ankle moment under this surface condition is warranted and may help further explaining the observed differences. The results from this study suggest that the testing method uring landing on a slant surface provides a better testing protocol for investigation of ankle sprain mechanisms compared to the landing on a flat surface as it imposes greater inversion and load to the ankle. Actual ankle sprains occur mostly during landing onto an uneven surface from a jump in sports [18].Wearing a brace did not cause any significant changes in the first and second peak vertical GRFs in both landing surface conditions. However, Hodgson and the colleagues found a significant increase in vertical GRF at toe contact during flat surface landing while wearing an ankle brace [18]. This increased vertical GRF has often been attributed to a decrease in sagittal-plane ROM due to the application of an ankle brace which restricts ankle ROM [18]. In our study, the application of the ankle brace placed ankle in a significantly less plantarflexed position at contact (a mean reduction of 12°) and introduced significantly less dorsiflexion ROM (a mean reduction of 8°) during the landing phase. In addition, the contact and maximum dorsiflexion velocities are significantlyreduced during the braced landing conditions. However, our peak GRF data was not increased in the slant surface conditions. Further investigation is needed to examine the relationship between peak GRF and sagittal ankle ROM.

Although the peak vertical peak GRFs were not changed wearing the brace, we did see a significantly shorter time to the 2nd peak vertical GRF for both slant surface and flat surface landing conditions with brace, which is also supported by the findings of Hodgson et al. observed an increased loading rate in the braced landing on flat surface. In our study, although the 2nd peak vertical GRF did not change significantly after wearing the ankle brace, the reduced time to this peak may imply an increased loading rate. Limited research has been conducted to evaluate the brace effects on the peak vertical GRFs and the times. Researchers concluded that ankle stabilizers shorten the time to reach the peak(s) [34], suggesting that lower extremity joints, especially the ankle joint, may be subjected to increased loading [34]. The lack of significant peak GRFs in our study may be related to the fact that the subjects we tested in the study were healthy without an ankle sprain within past 6 months. Those who sprained their ankle might react different to test conditions compared to healthy subjects. Less energy absorption by the ankle plantarflexors would occur during landings with ankles stabilized. Conversely, a greater energy transfer from ankle musculature while wearing ankle brace up to the leg would probably increase the demand on knee and hip joints to absorb energy [26]. However, the results do not support our initial hypothesis. Further examination of ankle as well as knee and hip kinetics (and kinematics) may help further explaining the results of the peak GRFs.

Brace effects on frontal plane kinematics are quite significant and widespread in the slant surface landing compared to the regular landing. Ankle brace restricted the contact and maximum inversion angle in the slant surface landing. These findings are supported by Eils's conclusion that ankle brace reduced the maximum inversion through the mechanism that it controls the joint position before landing [14]. The ankle brace caused a significantly reduced contact velocity in the flat surface landing and reduced maximum eversion velocity in both landing protocols. These findings coincided with majority studies which found significant brace effect on the inversion drop device [2, 14, 32, 33]. Contrary to our initial hypothesis, the ankle brace increased the contact ($p<0.05$) and maximum inversion velocities (not statistically significant) during slant surface landing, only the maximum eversion angular velocity was decreased. This implied that the Element ankle brace is a semi-rigid brace with a heel stripping system. The brace application may increase the stiffness of the ankle complex and therefore may increase the contact and maximum inversion velocities

For the 1st peak lateral GRF, the brace did not affect this variable during flat and slant surface landing. As the brace application positions the foot in a less inverted and more neutral position at touchdown during flat surface landing may cause the center of gravity (COG) to be applied more medially on the foot plantar surface compared to the landing with no brace on the flat surface. Ankle brace not only affects ankle movement but also the joint(s) above it. With the application of the ankle brace, the ankle joint is locked and impact loading may be more likely to be transferred to cause a knee varus motion for the purpose of energy absorption and balance landing [45]. Venesky showed an existence of valgus torque in both brace and no brace conditions in landing on a slant surface [45]. An eccentric valgus torque indicates that varus motion is resisted by the lateral knee passive structures and muscles [45]. However this varus motion is not large enough to cause the unsustainable stress for the knee joints. A further examination of the knee and hip kinematic and kinetic variables of the current study would provide a more complete picture of landing strategy changes throughout the entire kinetic chain.

The ankle brace restricted the contact plantar flexion and dorsiflexion ROM in both landing conditions. Interestingly, McCaw and his colleagues showed reductions of 2 - 4° in plantarflexion angle at touchdown and 5 - 6° in dorsiflexion ROM in three common ankle braces compared with the Active ankle brace and no brace conditions [26]. In our study, however, the application of the semi-rigid Element ankle brace caused the ankle contact plantarflexion angle and dorsiflexion ROM to be reduced on average of 12° and 8°, respectively in both landing conditions. The difference between our study and McCaw's may be due to the difference of the landing protocols. In the study by McCaw et al., subjects were asked to step off from a 0.59 m platform, the initial ankle position was more dorsiflexed [26]. In our study, subjects were asked to land from the overhead hanging bar, the initial ankle position was more plantarflexed prior to the initiation of landing. MaCaw's study showed an average contact plantarflexion angle of 12° for the three common ankle braces, 13° for the Active ankle brace, and 15° for the no stabilizer condition. In our study, the contact plantarflexion angle were 18.5° (no brace) and 7.1° (brace) for the flat surface landing, and 17.9° (no brace) and 5° (brace) for the slant surface landing [26]. It is not clear that whether the initial resting foot position would affect the ankle position at touchdown or not. However, it is clear that the foot position at touchdown will affect the final foot position. Wright et al. found that the touchdown plantar flexion angle has a greater influence on the sprain occurrence than the touchdown supination (inversion) angle [47]. The difference in the initial foot position may also influence the energy absorption during the landing phase after foot contact as the amount of dorsiflexion ROM is closely related to the amount of energy absorption. As the Element ankle brace is a semi-rigid brace with a heel stripping system, it provides more restriction than other types of ankle brace [48] . The reduced contact ankle position may reduce the dorsiflexion ROM during the landing phase wearing the ankle brace, which in turn negatively influence energy absorption. However, the brace itself may help make up the difference in energy absorption by providing additional energy absorption during landing.

CONCLUSIONS

The results showed that the slant surface landing resulted in significantly earlier maximum inversion angle occurrence. Significantly higher maximum eversion and inversion velocities were also found in the slant surface landing compared to the inversion drop test. A lack of eversion and significant shorter time to reach the peak GRF and kinematic values were also found in the slant surface landing condition, suggesting that ankle musculature has less time to adjust to the impact loading. No significant difference was found for the contact plantarflexion angle between the slant surface landing and inversion drop test, however slant surface exhibited significant higher dorsiflexion range of motion (ROM), contact dorsiflexion velocity, and maximum dorsiflexion velocity compared to the inversion drop test.

The comparisons between flat and slant surface landings showed that slant surface landing induced significantly smaller peak vertical and lateral GRFs compared to landing on flat surface, and the lateral ankle ligaments are under a tighter and stretched status which allow the ligaments to contribute more to the impact attenuation. Flat surface landing enable individuals make foot contact more perpendicular to the landing surface, meanwhile induced significant higher dorsiflexion ROM, contact and maximum dorsiflexion velocities. Subjects adopted a slightly stiffer strategy when landing onto the slant surface.

These results suggest that the slant surface drop landing better simulated actual ankle sprain mechanism, and therefore, the hypotheses of the study were supported. More studies relating to the drop landing are warranted in future investigate not only the ankle joint kinematics and kinetics, but also the knee and hip joint kinematics and kinetics in order to provide a comprehensive picture of loading to the entire lower extremity kinetic chain during ankle sprain.

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APPENDICES

APPENDIX A

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE

Name:________________________________ Date(MM/DD/YY): : _____/_____/_____

Please answer the following questions to the best of your knowledge (circle YES or NO).

1. **Yes** **No** Has your doctor ever said you had heart trouble or a heart murmur?

2. **Yes** **No** Do you ever suffer pains in your chest?

3. **Yes** **No** Do you ever feel faint or have spells of severe dizziness, passed out, palpitations or rapid heart beat?

4. **Yes** **No** Has the doctor ever told you that your blood pressure was too high? (systolic $\geq$ 160 mm Hg or diastolic $\geq$ 90 mm Hg on at least 2 separate occasions)

5. **Yes** **No** Do you smoke cigarettes?

6. **Yes** **No** Do you have any neuropathy as a result of diabetes?

7. **Yes** **No** Do you have a family history of coronary or other atherosclerotic disease in parents or siblings prior to age 55?

8. **Yes** **No** Has your serum cholesterol ever been elevated?

9. **Yes** **No** Is there any physical reason not mentioned here why you should not follow an activity program even if you wanted to?

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

____

____

____

____

____

____

Participant initials___________

DEMOGRAPHIC QUESTIONNAIRE

Name ______________________________ Date (MM/DD/YY): _____/_____/_______

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

Gender: (check one) ☐ 1. Female ☐ 2. Male

Height: _____ Feet, _____ Inches or ________ cm

Weight: _________________lbs or _________ kg

Please Check One:

Do you use specialized insoles or foot orthotics? ☐ 0. NO ☐ 1. Yes

Do you have any injuries that may affect the way you walk or run: ☐ 0. NO ☐ 1. Yes

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

____

____

____

Have you injured your lower extremities in the last year: ☐ 0. NO ☐ 1. Yes

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

____

____

Participant initials___________

INFORMED CONSENT FORM

Investigator: Qingjian Chen B.S.
Address: Biomechanics/Sports Medicine Lab
The University of Tennessee
1914 Andy Holt Avenue
Knoxville, TN 37996
Phone: (865) -974-8768

Introduction

You are invited to participate in a research study entitled, "Biomechanical Evaluation of Two Ankle Inversion Testing Protocols: Trapdoor and Drop Landing". The purpose of this study is to examine the differences of two ankle brace testing methods while wearing an ankle brace in controlling ankle motions. This consent form may contain words that you do not understand. Please ask the study staff to explain any words or information that you do not clearly understand. Before agreeing to be in this study, it is important that you read and understand the following explanation of the procedures, risks, and benefits.

Testing Protocol and Duration

You will be asked to attend one test session that will take approximately 1.5 hours to complete. At the beginning of the test session, you will be asked to read and sign this Informed Consent Statement before participating in the testing session. At the beginning, you will fill out a questionnaire about your age, height, weight, and injury history, and a physical activity readiness questionnaire. Afterwards, a measurement of your height and body weight, the range of motion of your ankle movements without an ankle brace, and ankle joint neutral position with and without the ankle braces will be taken. The test session will begin with a warm-up on a treadmill and stretching. Ankle width with and without the brace will also be measured using a caliper. You will then perform five times in each of six movement/brace conditions: 25° ankle lateral drop on a platform with and without brace, drop landing from 0.45 m height onto a 25° slant surface with and without brace, and drop landing from 0.45m height onto a flat surface with and without ankle brace. You will be asked to practice with the testing protocols on the platform and in the drop landing until you feel comfortable with the ankle before actual measurements are taken. During the testing, biomechanics instruments will be used to obtain measurements. Some of these instruments will be placed/fixed on your body. None of the instruments will impede your ability to engage in normal and effective motions during the test. If you have any further questions, interests or concerns about any instrumentation, please feel free to ask the investigator.

Potential Risks

Risks associated with this study are minimal. A potential risk includes a lateral ankle sprain during the dynamic movements. The ankle inversion drop on the trap door and drop landing onto slant surface are two common testing procedures used in studies related to ankle movements and ankle braces. Ample practice will be provided for both movements and sufficient warmup is also required for you prior to the testing to minimize any possibility of soft tissue injuries due to lack of warmup. The investigator or other qualified research personnel in the Biomechanics/Sports Medicine Lab will be stationed close to you and provide assistance in case you lose balance. Should any injury occur during the course of testing, standard first aid procedures will be administered as necessary. At least one researcher with a basic knowledge of athletic training and/or first aid procedures will be present at each test session. The University of Tennessee does not "automatically" reimburse subjects for medical claims or other compensation. If physical injury is suffered in the course of research, or for more information, please notify the principal investigator at (865)-974-8768

Benefits of Participation
Your benefits include the opportunity for you to learn about how to control ankle motions during unbalanced movements to avoid a lateral ankle sprain and to learn about the effectiveness of an ankle brace in controlling ankle movements in injurious situations.

Compensation
There will be no compensation for your participation in this study.

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. It is your obligation to ask questions regarding any aspect of this study that you do not understand. You will have 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 investigator feels that it is in your best interest to stop participation.

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. Information from this study will be reviewed but will not be used for commercial purposes by the Sponsor. The results will be disseminated in the form of a technical report (to the sponsor), 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 at the conclusion of the study.

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

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

Subject's Name: ________________________ Signature: ________________________ Date:

Investigator's Signature: _________________________ Date: ___________________

Subject Number ___________ **(Please Print Clearly)**

Participant initials___________

APPENDIX B

Table 5. Descriptive Characteristics

Subject	Gender (F/M)	Age (years)	Height (meters)	Weight (kilograms)
3	M	33	1.83	74.39
4	M	27	1.66	58.2
6	M	29	1.87	83.6
7	M	31	1.66	63.05
8	M	21	1.77	69.85
9	F	26	1.69	75.3
10	M	27	1.81	87.09
11	F	24	1.59	49.44
12	F	23	1.59	56.7
13	F	28	1.55	59.87
14	F	21	1.66	49.89
Mean		26.34	1.70	66.13
(SD)		3.88	0.11	12.86

Table 6. Subject means and standard deviations of peak vertical and horizontal ground reaction forces.

Subj	Cond	F1_Z	TF1_Z	F2_Z	TF2_Z	FMin1_X	TFMin1_X	FMin2_X	TFMin2_X
3	LF_NB	0.929±0.137	0.010±0.002	2.903±0.460	0.044±0.006	-0.113±0.018	0.013±0.002	-0.300±0.038	0.046±0.010
	LF_BR	0.845±0.209	0.006±0.002	3.045±0.147	0.033±0.003	-0.289±0.060	0.034±0.004	-0.138±0.016	0.131±0.011
	LS_NB	--	--	2.282±0.193	0.038±0.001	-0.005±0.150	0.021±0.013	-0.289±0.093	0.058±0.028
	LS_BR	0.661±0.071	0.011±0.002	2.617±0.541	0.045±0.007	0.010±0.017	0.016±0.002	-0.188±0.079	0.054±0.008
4	LF_NB	0.706±0.095	0.006±0.001	3.722±0.418	0.029±0.005	-0.219±0.043	0.017±0.004	-0.240±0.032	0.030±0.004
	LF_BR	1.378±0.186	0.007±0.001	3.757±0.766	0.034±0.003	-0.205±0.027	0.023±0.023	-0.285±0.072	0.058±0.042
	LS_NB	0.624±0.109	0.009±0.002	2.996±0.291	0.031±0.004	-0.181±0.200	0.022±0.008	-0.227±0.073	0.063±0.029
	LS_BR	0.859±0.049	0.008±0.002	2.482±0.196	0.034±0.004	0.046±0.059	0.013±0.002	-0.357±0.043	0.041±0.003
6	LF_NB	1.433±0.145	0.015±0.001	2.846±0.545	0.058±0.005	-0.195±0.044	0.015±0.001	-0.355±0.027	0.048±0.003
	LF_BR	1.454±0.149	0.010±0.003	3.631±0.516	0.043±0.004	-0.158±0.018	0.014±0.002	-0.308±0.069	0.040±0.002
	LS_NB	--	--	3.277±0.195	0.044±0.004	-0.088±0.014	0.020±0.006	-0.145±0.021	0.055±0.006
	LS_BR	--	--	3.269±0.236	0.037±0.004	-0.009±0.018	0.015±0.001	-0.143±0.032	0.050±0.005
7	LF_NB	1.254±0.099	0.010±0.002	3.927±0.634	0.046±0.004	-0.181±0.056	0.012±0.001	-0.135±0.036	0.037±0.003
	LF_BR	1.292±0.089	0.009±0.001	4.238±0.322	0.039±0.002	-0.191±0.042	0.012±0.001	-0.177±0.091	0.037±0.001
	LS_NB	1.064±0.067	0.012±0.002	3.703±0.295	0.049±0.003	-0.043±0.016	0.019±0.002	-0.191±0.028	0.072±0.003
	LS_BR	0.878±0.046	0.010±0.002	3.865±0.310	0.034±0.003	0.003±0.022	0.014±0.002	-0.155±0.019	0.077±0.015

Table 6. Continued.

Subj	Cond	F1_Z	TF1_Z	F2_Z	TF2_Z	FMin1_X	TFMin1_X	FMin2_X	TFMin2_X
8	LF_NB	1.288±0.085	0.011±0.002	3.884±0.427	0.049±0.001	-0.200±0.033	0.014±0.003	-0.445±0.038	0.047±0.002
	LF_BR	1.032±0.130	0.007±0.002	3.995±0.453	0.038±0.004	-0.185±0.021	0.015±0.002	-0.410±0.068	0.037±0.003
	LS_NB	0.841±0.055	0.012±0.001	3.130±0.391	0.058±0.003	-0.069±0.010	0.027±0.010	-0.280±0.106	0.064±0.006
	LS_BR	0.690±0.102	0.011±0.001	2.987±0.125	0.051±0.005	-0.011±0.023	0.020±0.005	-0.353±0.078	0.056±0.005
9	LF_NB	1.458±0.113	0.013±0.001	2.812±0.145	0.056±0.003	-0.307±0.077	0.034±0.025	-0.329±0.093	0.098±0.045
	LF_BR	1.237±0.128	0.008±0.002	3.088±0.451	0.042±0.004	-0.387±0.040	0.040±0.018	-0.257±0.071	0.131±0.049
	LS_NB	0.770±0.051	0.013±0.001	2.534±0.253	0.055±0.003	-0.114±0.008	0.037±0.002	-0.274±0.052	0.064±0.003
	LS_BR	0.545±0.024	0.009±0.001	2.270±0.097	0.035±0.007	-0.014±0.072	0.014±0.002	-0.308±0.063	0.044±0.005
10	LF_NB	1.358±0.135	0.014±0.002	2.083±0.497	0.059±0.007	-0.267±0.073	0.035±0.021	-0.291±0.087	0.092±0.045
	LF_BR	1.309±0.035	0.010±0.002	2.211±0.253	0.049±0.003	-0.385±0.039	0.050±0.012	-0.235±0.026	0.152±0.009
	LS_NB	0.986±0.101	0.013±0.002	2.250±0.305	0.057±0.008	-0.208±0.020	0.060±0.007	-0.156±0.028	0.135±0.033
	LS_BR	1.042±0.002	0.016±0.004	2.147±0.308	0.048±0.007	-0.152±0.111	0.039±0.026	-0.236±0.079	0.087±0.049
11	LF_NB	1.262±0.073	0.013±0.002	2.485±0.254	0.065±0.006	-0.265±0.048	0.013±0.002	-0.320±0.060	0.068±0.014
	LF_BR	1.386±0.167	0.011±0.002	2.018±0.352	0.057±0.011	-0.220±0.026	0.012±0.002	-0.389±0.065	0.063±0.012
	LS_NB	1.000±0.075	0.012±0.003	1.888±0.134	0.061±0.008	-0.045±0.054	0.014±0.002	-0.133±0.063	0.057±0.009
	LS_BR	1.280±0.154	0.014±0.002	1.992±0.227	0.054±0.008	-0.039±0.036	0.024±0.010	-0.213±0.056	0.061±0.008

Table 6. Continued.

Subj	Cond	F1_Z	TF1_Z	F2_Z	TF2_Z	FMin1_X	TFMin1_X	FMin2_X	TFMin2_X
12	LF_NB	1.360±0.241	0.011±0.001	3.623±0.300	0.048±0.001	-0.174±0.036	0.013±0.001	-0.399±0.081	0.051±0.009
	LF_BR	1.182±0.173	0.008±0.002	3.809±0.398	0.036±0.003	-0.216±0.018	0.014±0.002	-0.367±0.044	0.038±0.004
	LS_NB	0.775±0.209	0.010±0.002	3.117±0.219	0.042±0.007	-0.067±0.053	0.026±0.009	-0.330±0.028	0.051±0.007
	LS_BR	--	--	2.496±0.238	0.034±0.002	0.083±0.079	0.014±0.001	-0.290±0.033	0.042±0.004
13	LF_NB	1.544±0.166	0.012±0.001	3.001±0.509	0.050±0.003	-0.249±0.039	0.014±0.001	-0.335±0.038	0.038±0.003
	LF_BR	1.771±0.135	0.009±0.001	3.327±0.754	0.038±0.002	-0.267±0.021	0.012±0.001	-0.288±0.059	0.037±0.002
	LS_NB	1.318±0.000	0.017±0.000	3.013±0.245	0.044±0.004	-0.116±0.023	0.030±0.005	-0.215±0.061	0.055±0.003
	LS_BR	--	--	2.789±0.187	0.038±0.003	-0.029±0.041	0.017±0.004	-0.298±0.025	0.048±0.005
14	LF_NB	1.483±0.443	0.010±0.004	3.862±0.531	0.032±0.011	-0.334±0.105	0.011±0.002	-0.253±0.113	0.033±0.007
	LF_BR	1.594±0.082	0.009±0.002	4.058±0.449	0.028±0.010	-0.341±0.073	0.010±0.002	-0.254±0.069	0.034±0.012
	LS_NB	1.174±0.036	0.015±0.001	3.263±0.167	0.033±0.007	-0.023±0.044	0.015±0.008	-0.118±0.092	0.041±0.009
	LS_BR	--	--	3.060±0.682	0.015±0.001	-0.151±0.041	0.032±0.004	0.000±0.049	0.077±0.011

Table 7. Subject means and standard deviations of frontal plane ankle angles.

Subj	Cond	Cont_Inv	Max_Inv	TMax_Inv	ROM	Max_Ev	TMax_Ev
3	LF_NB	6.024±2.004	4.809±0.453	0.044±0.006	-6.887±3.366	-0.864±3.113	0.194±0.084
	LF_BR	2.293±0.631	--	--	-6.353±1.517	-4.060±1.287	0.220±0.080
	LS_NB	5.530±0.956	27.323±1.398	0.059±0.002	21.793±1.047	--	--
	LS_BR	13.085±1.627	24.471±3.261	0.058±0.003	11.386±3.457	--	--
	ID_NB	3.697±0.698	--	--	16.968±1.744	1.660±1.045	0.049±0.003
	ID_BR	17.083±0.662	27.411±2.924	0.258±0.024	9.395±1.831	15.524±0.568	0.071±0.017
4	LF_NB	3.227±1.728	--	--	-11.277±2.035	-8.050±1.180	0.092±0.026
	LF_BR	4.480±0.880	--	--	-8.461±1.902	-3.982±1.859	0.133±0.044
	LS_NB	13.049±3.030	22.170±2.596	0.041±0.005	9.121±2.427	--	--
	LS_BR	10.801±3.548	21.729±3.603	0.047±0.005	10.927±2.150	--	--
	ID_NB	13.737±2.092	24.984±0.772	0.327±0.021	12.574±3.544	9.088±2.601	0.061±0.011
	ID_BR	6.167±0.703	25.976±2.992	0.199±0.012	18.578±2.363	5.126±0.480	0.039±0.006
6	LF_NB	5.641±2.423	4.690±2.268	0.018±0.013	-5.841±2.385	-0.040±1.487	0.099±0.024
	LF_BR	0.670±0.440	1.141±0.985	0.036±0.040	-3.249±3.410	-3.425±3.152	0.139±0.043
	LS_NB	15.589±1.328	23.184±2.504	0.051±0.005	7.595±1.766	--	--
	LS_BR	7.318±1.067	21.169±0.850	0.056±0.005	13.962±0.775	--	--
	ID_NB	17.791±1.025	29.857±3.675	0.230±0.076	12.262±3.577	14.064±1.477	0.085±0.014
	ID_BR	2.933±0.009	19.285±2.260	0.263±0.041	15.755±1.194	-2.327±0.207	0.081±0.003
7	LF_NB	2.780±1.261	1.836±2.332	0.077±0.003	-2.896±1.537	-1.176±1.988	0.092±0.054
	LF_BR	1.877±1.342	0.970±1.844	0.074±0.010	-2.310±1.298	0.321±0.000	0.033±0.000
	LS_NB	10.923±1.036	25.019±1.939	0.072±0.002	14.095±1.666	--	--
	LS_BR	5.935±0.668	14.100±0.512	0.051±0.005	8.165±1.128	--	--
	ID_NB	9.288±1.846	27.061±1.446	0.206±0.012	16.134±1.886	8.104±2.151	0.033±0.005
	ID_BR	2.976±1.577	17.009±5.517	0.238±0.016	11.381±5.305	0.607±2.148	0.054±0.008

Table 7. Continued.

Subj	Cond	Cont_Inv	Max_Inv	TMax_Inv	ROM	Max_Ev	TMax_Ev
8	LF_NB	10.208±0.608	10.821±0.000	0.004±0.000	-6.672±1.764	2.907±0.980	0.108±0.008
	LF_BR	0.774±0.700	1.371±0.635	0.004±0.000	-5.872±1.130	-5.145±0.990	0.088±0.021
	LS_NB	12.418±0.974	25.348±1.624	0.068±0.003	12.929±2.383	--	--
	LS_BR	6.874±1.475	22.041±2.407	0.065±0.005	15.167±2.953	--	--
	ID_NB	15.047±0.636	29.335±1.892	0.238±0.038	13.224±1.110	11.359±2.158	0.071±0.004
	ID_BR	3.447±1.441	19.056±1.461	0.229±0.031	14.736±1.722	0.540±1.831	0.051±0.003
9	LF_NB	4.921±0.729	6.303±1.415	0.043±0.011	-2.234±1.245	2.687±1.011	0.112±0.011
	LF_BR	3.238±0.639	4.503±1.020	0.040±0.014	-1.831±2.004	1.407±1.596	0.097±0.015
	LS_NB	8.396±1.799	22.582±0.450	0.069±0.004	15.049±1.309	--	--
	LS_BR	8.296±1.915	24.011±0.953	0.051±0.006	15.715±2.454	--	--
	ID_NB	9.084±0.571	26.763±1.025	0.170±0.022	16.503±0.604	8.687±0.614	0.011±0.012
	ID_BR	2.917±0.423	21.139±2.001	0.212±0.015	17.987±2.474	1.397±1.038	0.039±0.006
10	LF_NB	8.326±1.067	8.706±1.362	0.023±0.017	-5.097±1.267	3.409±1.355	0.203±0.053
	LF_BR	1.371±0.972	1.927±1.126	0.136±0.061	-1.199±1.909	0.374±1.347	0.228±0.086
	LS_NB	15.182±3.504	27.698±2.621	0.068±0.007	12.515±1.828	--	--
	LS_BR	5.053±0.875	18.108±1.277	0.071±0.012	15.393±3.139	--	--
	ID_NB	14.757±1.653	31.702±1.167	0.228±0.049	15.512±2.683	14.929±1.609	0.016±0.011
	ID_BR	5.358±0.557	20.952±2.134	0.324±0.069	14.829±0.667	4.607±1.328	0.028±0.022
11	LF_NB	-1.998±2.293	-0.562±1.740	0.028±0.009	-6.105±4.209	-8.426±3.030	0.131±0.011
	LF_BR	3.324±0.797	7.479±2.425	0.059±0.011	-0.323±2.791	2.835±2.764	0.103±0.042
	LS_NB	8.437±2.056	21.530±1.474	0.069±0.008	13.093±2.489	--	--
	LS_BR	5.695±2.430	24.496±1.601	0.065±0.006	18.801±1.982	--	--
	ID_NB	9.123±0.788	18.090±3.839	0.305±0.037	9.012±3.775	10.084±2.164	0.146±0.092
	ID_BR	7.147±0.845	23.634±3.003	0.326±0.077	16.327±1.952	6.624±1.443	0.023±0.021

Table 7. Continued.

Subj	Cond	Cont_Inv	Max_Inv	TMax_Inv	ROM	Max_Ev	TMax_Ev
12	LF_NB	8.972±2.464	9.925±2.159	0.023±0.024	-5.145±4.033	3.826±4.830	0.111±0.027
	LF_BR	7.255±0.373	7.929±0.391	0.038±0.017	-1.915±0.515	5.353±0.333	0.097±0.003
	LS_NB	12.766±3.393	35.180±2.013	0.065±0.008	22.470±1.627	--	--
	LS_BR	13.126±1.554	34.722±1.400	0.050±0.003	21.596±1.732	--	--
	ID_NB	18.707±1.630	40.762±3.823	0.239±0.022	19.889±5.809	16.421±1.703	0.051±0.020
	ID_BR	8.762±0.793	32.052±2.689	0.199±0.112	19.855±3.134	7.688±0.944	0.042±0.008
13	LF_NB	5.550±0.674	5.252±1.242	0.022±0.035	-10.354±1.992	-4.804±2.050	0.183±0.019
	LF_BR	-1.256±0.463	-0.714±0.546	0.022±0.021	-3.247±1.946	-4.535±1.992	0.138±0.063
	LS_NB	12.631±0.836	25.187±5.052	0.057±0.007	12.556±4.388	--	--
	LS_BR	4.931±0.825	24.785±4.335	0.054±0.004	19.854±4.135	--	--
	ID_NB	12.463±4.305	21.654±1.819	0.220±0.087	8.906±5.089	9.667±4.780	0.108±0.141
	ID_BR	8.159±7.353	16.996±3.420	0.239±0.065	9.395±6.613	10.508±7.855	0.098±0.058
14	LF_NB	7.464±1.596	0.612±0.000	0.138±0.000	-11.246±2.539	-3.464±1.512	0.133±0.036
	LF_BR	0.332±1.186	-8.290±0.000	0.342±0.000	-9.655±1.712	-9.323±1.154	0.155±0.030
	LS_NB	15.252±2.366	21.936±1.929	0.041±0.006	6.684±1.429	--	--
	LS_BR	11.754±1.549	18.877±3.157	0.033±0.002	7.123±1.853	--	--
	ID_NB	11.585±1.734	26.999±2.196	0.225±0.050	11.280±5.653	8.094±3.695	0.047±0.008
	ID_BR	7.490±4.649	18.975±2.612	0.168±0.067	14.461±1.671	4.871±5.512	0.084±0.069

Table 8. Subject means and standard deviations of frontal plane ankle velocities.

Subj	Cond	Cont_V	Max_Ev_V	TMax_Ev_V	Max_Inv_V	Tmax_Inv_V
3	LF_NB	-43.962±28.531	-153.268±51.937	0.078±0.005	--	--
	LF_BR	-10.538±17.355	-104.416±9.082	0.067±0.004	--	--
	LS_NB	380.884±11.350	-86.305±58.136	0.099±0.061	591.876±37.833	0.024±0.002
	LS_BR	185.264±73.522	-135.812±13.543	0.082±0.007	331.988±106.811	0.027±0.005
	ID_NB	-62.302±25.401	-69.056±27.804	0.016±0.003	150.074±21.130	0.236±0.008
	ID_BR	30.161±51.664	-86.756±6.687	0.034±0.009	9.400±38.541	0.298±0.092
4	LF_NB	-191.818±64.554	-249.165±23.341	0.038±0.026	--	--
	LF_BR	-132.020±23.701	-155.733±29.800	0.015±0.002	--	--
	LS_NB	266.509±121.758	-215.222±65.207	0.059±0.008	347.817±105.558	0.017±0.004
	LS_BR	273.975±59.473	-109.042±31.804	0.062±0.006	381.130±51.647	0.019±0.004
	ID_NB	-73.978±42.721	-172.981±40.782	0.031±0.008	182.018±50.113	0.161±0.015
	ID_BR	-33.898±9.806	-35.472±10.813	0.008±0.007	-0.305±16.038	0.338±0.043
6	LF_NB	-44.884±34.399	-173.079±47.151	0.048±0.005	--	--
	LF_BR	11.700±28.969	-83.854±37.095	0.043±0.006	--	--
	LS_NB	104.439±15.981	-100.331±33.812	0.067±0.005	141.090±14.798	0.015±0.004
	LS_BR	306.820±52.479	-53.899±19.506	0.082±0.030	387.337±43.114	0.018±0.002
	ID_NB	153.305±27.090	-204.616±51.853	0.058±0.007	76.307±89.089	0.303±0.054
	ID_BR	-56.303±5.022	-89.650±6.818	0.052±0.003	15.595±12.515	0.363±0.053
7	LF_NB	-248.643±11.196	-343.232±19.940	0.020±0.002	--	--
	LF_BR	-145.739±25.965	-183.992±32.291	0.016±0.002	--	--
	LS_NB	11.258±41.408	-115.385±28.512	0.089±0.007	168.843±54.892	0.039±0.004
	LS_BR	101.653±26.086	-116.068±33.671	0.062±0.005	150.440±45.195	0.020±0.005
	ID_NB	-132.063±14.083	-154.191±15.714	0.014±0.002	211.815±27.731	0.132±0.016
	ID_BR	-43.079±24.137	-48.956±28.270	0.018±0.009	54.510±107.989	0.279±0.110

Table 8. Continued.

Subj	Cond	Cont_V	Max_Ev_V	TMax_Ev_V	Max_Inv_V	Tmax_Inv_V
8	LF_NB	-204.959±46.868	-280.971±65.435	0.021±0.003	--	--
	LF_BR	-60.453±24.331	-111.448±19.552	0.034±0.015	--	--
	LS_NB	58.536±24.972	-155.547±30.830	0.088±0.005	243.766±77.470	0.036±0.004
	LS_BR	159.939±43.923	-68.388±19.150	0.083±0.008	385.899±61.507	0.033±0.005
	ID_NB	-8.432±53.514	-218.428±51.913	0.040±0.007	200.271±64.265	0.133±0.027
	ID_BR	-88.830±6.101	-98.327±10.029	0.016±0.002	6.146±6.581	0.328±0.025
9	LF_NB	-60.654±32.345	-140.299±34.316	0.046±0.022	--	--
	LF_BR	-58.366±24.294	-140.050±54.846	0.049±0.026	--	--
	LS_NB	118.521±19.177	-75.005±7.679	0.082±0.004	245.156±51.187	0.033±0.003
	LS_BR	317.698±63.532	-162.872±33.008	0.063±0.006	415.239±27.778	0.018±0.006
	ID_NB	-25.999±35.515	-88.308±43.594	0.031±0.007	236.619±11.280	0.105±0.010
	ID_BR	-48.791±23.949	-58.863±25.008	0.011±0.005	57.127±72.851	0.248±0.126
10	LF_NB	-51.300±24.089	-211.423±37.645	0.051±0.005	--	--
	LF_BR	-18.889±38.074	-64.627±39.263	0.053±0.034	--	--
	LS_NB	146.085±43.739	-84.008±38.241	0.090±0.008	228.302±42.827	0.023±0.005
	LS_BR	129.488±32.616	-32.956±30.723	0.080±0.013	265.505±34.143	0.028±0.005
	ID_NB	-18.611±31.156	-43.168±31.593	0.017±0.004	143.469±18.445	0.130±0.022
	ID_BR	-22.461±32.736	-37.557±38.117	0.053±0.074	85.459±46.790	0.247±0.069
11	LF_NB	-165.550±50.861	-295.137±42.586	0.029±0.005	--	--
	LF_BR	-13.925±49.450	-75.803±51.098	0.037±0.039	--	--
	LS_NB	14.671±55.561	-168.759±75.159	0.093±0.009	88.732±84.146	0.036±0.006
	LS_BR	176.046±30.767	-177.597±53.381	0.085±0.010	330.148±68.232	0.028±0.003
	ID_NB	20.183±42.541	-23.928±47.309	0.045±0.032	65.224±23.556	0.238±0.021
	ID_BR	-12.947±22.311	-6.712±40.770	0.075±0.044	117.441±41.988	0.186±0.123

Table 8. Continued.

Subj	Cond	Cont_V	Max_Ev_V	TMax_Ev_V	Max_Inv_V	Tmax_Inv_V
12	LF_NB	-21.836±49.884	-132.291±62.852	0.067±0.026	--	--
	LF_BR	8.580±23.475	-91.056±33.362	0.062±0.023	--	--
	LS_NB	354.229±74.646	-99.032±46.913	0.078±0.011	519.872±45.377	0.025±0.005
	LS_BR	495.119±60.798	-162.560±33.633	0.061±0.004	652.200±58.674	0.020±0.002
	ID_NB	-20.735±37.076	-130.421±44.813	0.033±0.005	287.892±44.489	0.171±0.013
	ID_BR	-44.496±15.342	-22.359±50.264	0.038±0.036	151.108±62.802	0.147±0.063
13	LF_NB	-205.788±66.314	-347.568±110.562	0.027±0.002	--	--
	LF_BR	-102.026±80.172	-156.566±80.361	0.028±0.020	--	--
	LS_NB	113.234±82.070	-137.141±56.630	0.087±0.031	177.570±91.669	0.033±0.035
	LS_BR	287.225±42.463	-121.229±29.373	0.066±0.007	413.188±97.861	0.020±0.003
	ID_NB	6.030±96.003	-94.713±52.944	0.030±0.027	104.780±67.646	0.146±0.102
	ID_BR	72.759±102.455	-46.648±11.238	0.061±0.045	93.605±103.575	0.145±0.059
14	LF_NB	-158.700±40.855	-229.003±46.409	0.031±0.021	--	--
	LF_BR	-90.220±36.544	-149.502±33.002	0.028±0.009	--	--
	LS_NB	233.955±64.081	-192.292±26.865	0.061±0.009	258.847±58.961	0.013±0.005
	LS_BR	390.368±75.251	-133.923±50.164	0.048±0.002	390.655±75.315	0.005±0.002
	ID_NB	-132.184±30.202	-174.829±20.446	0.020±0.002	172.809±52.924	0.154±0.028
	ID_BR	59.147±169.944	-72.244±15.503	0.041±0.057	170.075±98.773	0.119±0.073

Table 9. Subject means and standard deviations of sagittal plane ankle angles and velocities.

Subj	Cond	Cont_PF	ROM_DF	Cont_DF_V	Max_DF_V	TMax_DF_V
3	LF_NB	-8.022±5.691	43.681±7.349	489.328±75.238	716.723±113.766	0.022±0.002
	LF_BR	-4.979±2.804	33.989±3.356	391.234±48.647	518.139±81.218	0.018±0.002
	LS_NB	-4.275±1.119	28.009±4.175	204.416±32.523	421.077±31.148	0.032±0.002
	LS_BR	-8.902±2.835	30.541±2.459	387.036±32.890	565.839±40.675	0.025±0.000
	ID_NB	-6.261±0.720	7.570±2.777	59.636±30.644	85.674±35.612	0.022±0.005
	ID_BR	-16.753±0.256	18.241±4.654	33.542±29.518	235.540±26.744	0.030±0.002
4	LF_NB	-5.966±4.737	32.351±3.624	477.075±65.791	560.499±103.252	0.017±0.003
	LF_BR	-5.528±3.424	29.556±5.260	477.780±43.870	623.751±69.689	0.019±0.002
	LS_NB	-8.800±2.974	33.004±4.431	323.129±85.312	502.082±80.210	0.025±0.003
	LS_BR	-0.969±2.729	25.639±4.797	273.202±24.764	439.929±50.459	0.025±0.003
	ID_NB	-22.465±1.210	24.873±1.636	-17.219±5.604	184.508±44.442	0.044±0.014
	ID_BR	-4.337±1.280	8.278±1.881	13.945±34.203	80.981±24.325	0.111±0.035
6	LF_NB	-16.738±2.133	37.014±1.511	381.463±46.188	759.635±27.054	0.028±0.002
	LF_BR	-14.460±4.380	30.309±3.976	397.094±22.221	640.294±55.389	0.023±0.002
	LS_NB	-18.658±2.751	34.496±2.686	458.421±66.293	698.738±58.319	0.023±0.002
	LS_BR	-10.293±2.126	21.714±3.250	266.131±56.177	461.143±82.926	0.025±0.000
	ID_NB	-23.557±1.016	16.683±0.562	-141.242±47.787	191.873±14.786	0.054±0.019
	ID_BR	-9.621±0.574	6.790±0.819	29.960±14.102	50.195±15.316	0.019±0.003
7	LF_NB	-24.396±1.971	46.814±2.554	596.701±32.706	857.074±47.195	0.022±0.002
	LF_BR	-11.995±1.120	39.522±2.129	488.166±29.810	694.671±40.459	0.021±0.000
	LS_NB	-28.038±1.180	41.810±3.629	495.153±29.407	814.863±30.955	0.027±0.002
	LS_BR	-11.646±1.840	35.509±1.763	352.833±26.081	543.469±33.456	0.025±0.000
	ID_NB	-16.510±1.396	9.050±0.847	96.708±8.470	169.048±11.168	0.023±0.002
	ID_BR	-3.325±1.417	-2.961±5.201	12.227±33.424	58.731±26.807	0.121±0.089

Table 9. Continued.

Subj	Cond	Cont_PF	ROM_DF	Cont_DF_V	Max_DF_V	TMax_DF_V
8	LF_NB	-24.032±2.603	45.450±2.284	532.548±31.097	814.269±41.654	0.022±0.002
	LF_BR	-9.020±2.654	32.710±2.525	495.368±32.425	638.549±53.590	0.018±0.002
	LS_NB	-28.831±1.024	42.740±1.172	376.929±37.036	760.177±10.648	0.029±0.000
	LS_BR	-12.555±1.311	33.943±2.340	326.725±43.312	570.196±46.618	0.028±0.002
	ID_NB	-24.070±2.060	19.452±4.093	9.798±39.650	236.004±17.460	0.037±0.006
	ID_BR	-5.640±0.913	6.547±1.835	91.950±18.655	111.521±15.677	0.018±0.006
9	LF_NB	-28.180±2.226	54.782±2.151	525.155±35.251	972.284±45.120	0.027±0.002
	LF_BR	-12.594±1.787	38.589±1.998	531.910±38.289	745.257±43.672	0.021±0.000
	LS_NB	-24.910±1.685	37.705±4.359	412.855±62.087	739.977±48.144	0.027±0.002
	LS_BR	-7.763±3.511	24.280±0.713	319.572±24.513	486.026±33.493	0.024±0.003
	ID_NB	-22.458±1.564	19.090±2.404	66.407±42.608	285.913±48.094	0.037±0.003
	ID_BR	-3.124±0.702	5.046±2.370	14.566±17.596	85.851±18.140	0.098±0.025
10	LF_NB	-24.068±0.756	47.881±0.841	368.919±46.584	746.639±44.642	0.030±0.003
	LF_BR	-9.567±1.742	37.062±1.175	353.873±42.819	607.964±19.037	0.026±0.003
	LS_NB	-22.027±2.879	35.501±2.877	357.156±34.397	669.562±28.599	0.028±0.003
	LS_BR	-9.927±1.297	27.843±3.065	233.947±24.964	441.602±61.481	0.030±0.002
	ID_NB	-23.324±2.421	14.067±3.275	-1.532±18.985	110.869±46.271	0.028±0.009
	ID_BR	-6.588±1.862	0.977±2.323	-8.392±17.946	46.506±12.829	0.158±0.044
11	LF_NB	-23.228±2.223	54.297±4.562	573.851±50.833	915.312±30.717	0.024±0.002
	LF_BR	-7.389±3.421	44.662±5.524	571.302±11.113	851.252±58.270	0.024±0.002
	LS_NB	-20.468±2.246	36.699±3.550	453.642±49.304	755.858±47.195	0.025±0.003
	LS_BR	-5.382±1.881	33.639±3.365	437.316±32.197	713.084±49.644	0.026±0.002
	ID_NB	-16.795±3.596	16.487±3.038	41.536±42.034	181.029±39.352	0.028±0.003
	ID_BR	-1.531±1.056	5.514±0.618	18.955±24.009	70.807±18.403	0.093±0.080

Table 9. Continued.

Subj	Cond	Cont_PF	ROM_DF	Cont_DF_V	Max_DF_V	TMax_DF_V
12	LF_NB	-22.248±2.978	50.657±7.432	559.038±45.975	900.926±117.723	0.023±0.002
	LF_BR	-8.718±2.774	39.896±2.630	408.979±46.005	603.598±58.837	0.021±0.003
	LS_NB	-17.048±4.957	37.120±6.426	382.471±69.258	672.057±134.525	0.026±0.002
	LS_BR	-3.803±2.257	29.426±2.934	278.732±36.845	466.787±8.416	0.028±0.003
	ID_NB	-23.327±3.701	20.978±6.010	-6.611±19.655	236.595±60.336	0.059±0.016
	ID_BR	-7.484±0.509	5.334±2.126	57.365±29.033	86.150±23.993	0.046±0.031
13	LF_NB	-23.005±0.954	43.089±4.503	566.716±27.612	875.944±59.430	0.023±0.002
	LF_BR	-1.028±0.483	32.398±6.175	532.833±47.528	710.729±76.876	0.019±0.002
	LS_NB	-22.222±0.886	35.639±3.447	528.212±30.263	800.430±85.378	0.023±0.002
	LS_BR	-2.474±0.900	31.835±1.859	450.475±40.671	687.895±56.426	0.025±0.000
	ID_NB	-22.706±5.688	20.624±7.613	80.781±117.093	304.752±63.843	0.044±0.031
	ID_BR	7.152±2.740	8.257±5.639	59.168±50.849	154.631±34.697	0.050±0.038
14	LF_NB	-3.219±11.570	31.800±7.589	434.811±158.944	552.933±251.970	0.018±0.003
	LF_BR	6.996±7.836	28.342±7.664	317.592±195.475	446.440±174.391	0.033±0.031
	LS_NB	-1.937±4.213	25.938±5.479	340.421±79.470	449.424±126.645	0.022±0.003
	LS_BR	18.657±2.571	14.634±5.414	49.928±84.540	173.009±59.045	0.026±0.003
	ID_NB	-13.787±7.734	14.933±9.890	94.023±19.788	167.241±35.107	0.019±0.010
	ID_BR	2.917±4.153	5.798±3.691	50.321±25.158	91.308±39.058	0.055±0.050

VITA

Qingjian Chen was born in Nanjing, China on July 19, 1984 to the parents of Youdian Chen and Xiulan Zhang. She is the only daughter. She attended elementary school and junior high school in Nanjing. She graduated from No. 9 high school in Nanjing in 2002. From there, she went to Nanjing University of Sports where she was introduced to sports medicine and biomechanics. Qingjian completed sports medicine and rehabilitation program with Professor Jingguang Qian, which was an exciting and challenging experience and pushed her into continuing her education abroad. She obtained a Bachelor of Science degree from Nanjing University of Sports in 2006.She accepted a graduate teaching assistantship at The University of Tennessee, Knoxville, in the physical Education and Activities Program. Qingjian graduated with a Master of Science degree in exercise science with a concentration in biomechanics in 2009.