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Effect of Tilted surfaces on Ankle Kinematics and EMG activities in landing

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To the Graduate Council:

I am submitting herewith a thesis written by Divya Bhaskaran entitled "Effect of Tilted surfaces on Ankle Kinematics and EMG activities in landing." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Exercise Science.

Songning Zhang, Major Professor

We have read this thesis and recommend its acceptance:

Songning Zhang, Clare Milner, Eugene Fitzhugh

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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

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EFFECT OF TILTED SURFACES ON ANKLE KINEMATICS AND EMG ACTIVITIES IN LANDING

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

Divya Bhaskaran

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ABSTRACT

The purpose of this study was to examine the effects of landing on a combined inverted and plantarflexed surface on the ankle kinematics and electromyographic (EMG) activities of the medial gastrocnemius (MG), peroneal longus (PL) and anterior tibialis muscles (TA). Twelve recreational athletes performed five drop landings from an overhead bar of 30 cm height on to each of these surfaces: a flat surface, a 25° inversion surface (inverted), and a combined surface (combined) of 25° inversion and 25° plantarflexion. The three dimensional kinematic variables and integrated EMG (IEMG) of the three muscles were assessed using one-way repeated measures analysis of variance (ANOVA, $p < 0.05$) and a 3 × 3 (surface × muscle) ANOVA, respectively. The IEMG results showed a significant muscle by surface interaction. The flat surface induced higher TA activity than the two tilted surfaces. The inverted surface produced significantly higher inversion peak angle and velocity than the flat surface, but similar PL activity across the surfaces. The MG IEMG and ankle plantarflexion angle were significantly higher for the combined surface compared to the inverted surface. These findings suggest that compared to inversion, a combination of plantarflexion and inversion provides a more realistic surface for simulating lateral ankle sprains.

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CHAPTER I

INTRODUCTION

Ankle sprains are the most predominant type of injuries occurring in sports such as football and basketball (Fong et al., 2007; Hootman et al., 2007). The injury rates reported for both sports were 1.34 per 1000 athlete exposures (Hootman et al., 2007). Poorly executed landing or cutting maneuvers on an irregular surface can both be factors causing ankle sprains (Garrick, 1977). Ankle sprains can occur by contact or non-contact mechanisms, 77% of all non-contact ankle sprains occur during landing or cutting movements (Kofotolis and Kellis, 2007). A history of ankle sprain injury was also shown to influence the re-occurrence of the injury estimated at a rate of 17.3% (Kofotolis and Kellis, 2007). In addition, neuromuscular strength and reaction time of the ankle muscles appear to influence the occurrence of ankle sprains (Baumhauer et al., 1995; Beynnon et al., 2001).

The typical mechanism of ankle sprain includes excessive inversion and plantarflexion of the ankle joint (Garrick, 1977). Anatomically, the relative shortness of the medial malleolus, and the natural preference for the ankle to go into inversion rather than eversion usually results in a lateral ankle sprain (Garrick, 1977). Also the tendency of the foot to be in a more plantarflexed position at touchdown may cause an increased rate of ankle sprains (Wright et al., 2000) . The lower extremity joints undergo a few phases of change while landing from a jump. Soon after the takeoff, the lower extremity joints reach their largest extension. Thus, the joints are already slightly flexed before touchdown at landing. During the early part of ground contact phase, there is simultaneous flexion of the hip, knee and ankle joints. Two distinct characteristics of the prelanding patterns include reaching maximum extension of the limb before touchdown, and onset of contraction of all the leg musculature before landing, in a distal to proximal sequence, commencing with the ankle, followed by the knee and hip musculature (McKinley and Pedotti, 1992).

The positioning of the ankle can be affected by the muscle activity of the lower extremities such as medial gastrocnemius (MG), peroneus longus (PL), and tibialis anterior (TA) which are capable of stabilizing the joints and actively restricting the maximal motion by means of higher activation levels before and after touchdown (Arampatzis et al., 2003). Hence many studies investigated the electromyographic (EMG) activity of the lower extremity muscles during landing. TA acts as an ankle dorsiflexor and invertor, PL functions as an ankle plantar flexor and evertor, and MG is the one of the main plantarflexors and serves as the main shock absorption muscle on landing (Fu et al., 2007). The EMG activity in MG before landing is thought to be a pre-programmed, feed-forward response that serves to stiffen the ankle when a landing is anticipated, in order to cushion the impact (Funase et al., 2001). The role of TA is present during the pre- landing period. It demonstrates a burst-like activity and peaks during the ground contact and stabilization phase (McKinley and Pedotti, 1992). PL demonstrates an increased myoelectrical activity during the landing phase (Arampatzis et al., 2003).

Researchers have examined extensively the effect of sudden inversion stress on the neuromuscular activity of the ankle muscles (Lynch et al., 1996; Ebig et al., 1997; Cordova et al., 1998; Alt et al., 1999; Cordova and Ingersoll, 2003; Schmidt et al., 2005; Ty Hopkins et al., 2007; Kernozek et al., 2008). These studies have measured the reaction time of the muscles and the magnitude of the EMG activity during sudden inversion perturbation. The reaction time or latency, defined as the time between the beginning of the inversion and the onset of the first muscle response, provides the information about the amount of time needed for a muscle to respond to sudden inversion (Lynch et al., 1996). When subjected to a sudden 30° of inversion, the latency was 74 ms and 73 ms for PL and TA, respectively; the EMG magnitude was 310% and 76% of the maximum voluntary isometric contraction (MVIC) for PL and TA, respectively (Ty Hopkins et al., 2007). Some studies included a testing protocol that subjected the ankle to a combined stress of inversion and plantarflexion as it is closer to the actual sprain mechanism in sport activities (Ebig et al., 1997; Duncan and McDonagh, 2000). Ebig et al. subjected the ankle to a combined inversion and plantarflexion of 20° and observed a response time of 65 ms in PL and 71 ms in TA (Ebig et al., 1997). On the other hand, Lynch et al. conducted a study where the ankle was subjected to a plantarflexion perturbation of 20° (Lynch et al., 1996). This study illustrated a significant influence of the speed of plantarflexion on the reaction time of PL and TA muscles. TA responded quicker with latency of 92 ms at 200 deg/s of inversion speed compared to the latency of 106 ms at 50 deg/s. Similarly, PL had a shorter latency of 88 ms at the 200 deg/sec plantarflexion speed compared to 98 ms at 50 deg/s (Lynch et al., 1996).

As most ankle sprains occur in landing movements in sports, studies on the behavior of the ankle muscles during this movement contribute to providing additional information about the ankle sprain mechanism. During landing movements, TA and MG show preparatory activity 100 ms prior to ground contact (Funase et al., 2001). Moreover, there are studies that illustrated the varying EMG activity of TA, PL and MG with increasing landing height (Santello and McDonagh, 1998; Arampatzis et al., 2003; Hoffren et al., 2007). Arampatzis et al. demonstrated that the integrated EMG (IEMG) during pre-activation phase and landing phase, and EMG_{max} (maximum EMG activity) of PL, TA and MG had significantly higher values as the landing height increased from 1.0, 1.5 to 2.0 meters (Arampatzis et al., 2003). Nieuwenhuijzen et al. (Nieuwenhuijzen et al., 2002) and Gruneberg et al. (Gruneberg et al., 2003) studied the EMG activity of the PL, TA and MG muscles while an inversion perturbation was induced at the ankle using a trapdoor platform during step-off landing. Gruneberg et al. (Gruneberg et al., 2003) observed that the response amplitude of the PL was significantly less in the flat condition than in the inverting condition, while the TA and MG did not show significant differences.

Investigation of the ankle muscle activity when subjected to inversion perturbation during landing could provide realistic situations simulating the lateral ankle sprains compared to the inversion trap-door testing protocol (Zhang et al., 2009). Also, Lynch et.al., (Lynch et al., 1996) reported that the speed of inversion affects the muscle activity, and Nieuwenhuijezen et.al., (Nieuwenhuijzen et al., 2002) demonstrated that jumping on tilting surfaces provide higher tilting velocities (595 deg/s) than walking on tilting surfaces (403 deg/s). Hence, this study employs the drop landing protocol to study the lateral ankle sprain.

Furthermore, to the knowledge of the author no study measured the magnitude of the ankle muscle activity while being subjected to a combination of inversion and plantarflexion. Most studies only focused on static perturbation of the ankle, which is not the realistic nature of ankle sprains.

STATEMENT OF PROBLEM

Only a few studies have dealt with the EMG activity of the ankle in sprain simulating conditions such as tilted landing surfaces. These studies limited in number also do not provide sufficient information. There have been no studies focusing on tilted landing surface when the surface is a combination of inversion and plantarflexion. To the best of my knowledge, no studies have examined the issues that this study is concerned with, namely; combined tilted surface of inversion and plantarflexion.

PURPOSE

The main purpose of this study was to examine effects of landing surface inclination (flat, inversion alone, a combination of inversion and plantarflexion) on the ankle kinematics and EMG activity of PL, MG and TA muscles during drop landing movement.

SIGNIFICANCE OF STUDY

This study aims at providing more information on ankle muscle activity when the ankle is subjected to sprain simulating conditions. Using combined perturbations of inversion and plantarflexion would provide better insight on the muscle activity and the mechanism for ankle sprains during landing activity.

The following hypotheses were tested in this study:

1. Landing on an inverted surface and a combined inverted and plantarflexed surface would cause higher EMG magnitude and latency of the PL, TA and MG as compared to landing on a flat surface.
2. Landing on the combined inverted and plantarflexed surface would result in higher EMG magnitude and latency in the PL, TA and MG compared to landing on the inverted landing surface.
3. Landing on the combined inverted and plantarflexed surface would result in similar ankle inversion but greater plantarflexion than landing on the inverted surface.

LIMITATIONS

1. All the participants volunteered from a convenient sample of the students of the University of Tennessee.

2. The accuracy of the EMG recordings was limited by manual placement of the surface electrodes on the muscle bellies by palpation.

DELIMITATIONS

1. All participants were active, healthy and had no previous history of ankle sprains.
2. Each subject performed five trials in all three conditions with sufficient warm-up times.
3. Kinematics was collected at 240 Hz using a 3D camera motion analysis system (Vicon MX, Oxford. Metrics, Oxford, UK) and EMG activities were collected at 2400 Hz using an 8 channel surface electromyography system (2400 Hz, Noraxon USA, Inc., Scottsdale, AZ, USA).

CHAPTER II

LITERATURE REVIEW

The objective of this study was to determine the effects of landing surface inclination conditions (flat, inversion alone, a combination of inversion and plantarflexion) on the EMG activity of the PL, MG and TA muscles and ankle kinematics during a drop landing movement. Therefore, the literature review was focused on a survey of current knowledge of rates and mechanisms of ankle sprain injuries, the EMG activity while the ankle is subjected to inversion stress and the ankle muscle EMG activity and kinematics during landing.

RATE OF ANKLE INJURY AND ANKLE SPRAINS

Ankle Injury Rates

The ankle is ranked as one of the most commonly injured body sites (Garrick, 1977; Fong et al., 2007; Hootman et al., 2007; Kofotolis and Kellis, 2007). The injury rate of the joint is 12.3% in 24 sports in the United States (Fong et al., 2007). Garrick et al. (Garrick, 1977) reported 1,176 injuries of 2,840 participants in 14 sports, 14% of which involved the ankle joint, in a 2-year study of four high schools. During a 2-year prospective cohort study, Kofotolis and colleagues documented an ankle injury rate of 15.7% among 18 female Greek professional basketball athletes (Kofotolis and Kellis, 2007). Hootman et al. reported more than 27000 ankle ligament injuries accounting for 14.8% of all injuries registered in 15 sports over 16 academic years from the Injury Surveillance System (ISS) of US National Collegiate Athletic Association (NCAA) (Hootman et al., 2007).

Ankle injuries in sports are unique as the vast majority (85%) of injuries are sprains (Garrick, 1977). This was further supported by the ankle sprain prevalence rates of 76.7% in a meta-analysis study reported by Fong et al. (Fong et al., 2007), 64% reported by Kofotolis et al. (Kofotolis and Kellis, 2007), and 73.5% reported by Yeung (Yeung et al., 1994).

Interestingly, ankle sprain has a higher rate of occurrence in the dominant leg (36.6%) than in the non-dominant leg (15.3%) (Yeung et al., 1994). Yeung and the colleagues showed that, of 380 athletes with history of ankle sprains, 183 reported having bilateral ankle sprain, while 197 reported unilateral ankle sprain (Yeung et al., 1994). The relationship between the degree to which athletic performance is affected and the recurrence of ankle sprain was studied by Yeung et al., (Yeung et al., 1994). The author showed that 124 athletes reported to have five or more recurrences of the sprain, or 32.6% recurrent rate. The findings by Kofotolis et al. showed that 138 out of 204 participants had a previous ankle injury (Kofotolis and Kellis, 2007); of these 138, 64 players had a history of previous injury, and of these 64, 17.3% athletes had a recurrent injury while only 12.5% sustained a new ankle sprain.

Adverse effects of ankle sprains can be quantified by missed participation sessions and time lost (Kofotolis and Kellis, 2007). An injury rate of 0.8 per 1000 hours of exposure caused athletes to lose fewer than 7 sessions of practice among female Greek professional basketball players (Kofotolis and Kellis, 2007). Yeung et al observed residual symptoms such as pain, weakness, crepitus, instability, swelling, and stiffness with recurrence of ankle sprains (Yeung et al., 1994). The percentages of athletes complaining that the residual symptoms ‘often’ or ‘very often’ influence their athletic performance were 3.4% for the group with only one ankle sprain, 7.9% for the group with two to four ankle sprains, and 18.5% for the group with ankles sprained 5 or more times. The results show an influence of the increased recurrence of ankle sprains on the hindrance of athletic performance (Yeung et al., 1994).

Incidence of Ankle Sprains in Various Sports

The rate of ankle injury was much higher in games at 1.6 per 1000 hours of exposure than in practice sessions at 0.7 per 1000 hours of exposure (Kofotolis and Kellis, 2007). Fong and co-authors reported that during games, the incidence was highest in netball at 45.60 incidents per 1000 person hour followed by rugby of 8.88, football of 6.38, and basketball of 3.77 (Fong et al., 2007). Tennis had 11.3 incidents per 1000 person-exposure, followed by basketball at 9.1 and netball at 5.2. Hootman et al. reported a high rates of injury of 1.3 per 1000 athlete-exposure in both spring football and men's basketball from the NCAA injury data (Hootman et al., 2007).

Garrick et al., however, observed that men's and women's basketball have the highest ankle sprains at the rate of 38 and 45% of all injuries, respectively (Garrick, 1977). Women's cross country has the next highest frequency of sprains (Garrick, 1977). In sports such as Australian football, field hockey and squash, all the reported ankle injuries were ankle sprains (Fong et al., 2007). While, in sports like indoor volleyball, American football, basketball and netball greater than 80% of all ankle injuries were ankle sprains (Fong et al., 2007).

RISK FACTORS FOR ANKLE SPRAIN INJURY

Researchers believe that some of the risk factors for ankle sprain injury include foot and ankle positioning, muscle strength and reaction time (Baumhauer et al., 1995; Wright et al., 2000; Beynnon et al., 2001). Beynnon et al. through a prospective study on college athletes suggested that the orientation of the hind foot is an important parameter to consider when evaluating risk factors for ankle inversion trauma (Beynnon et al., 2001). Wright et al. observed the influence of foot positioning on ankle sprains and found that one of the factors contributing to the ankle sprain is inability position the foot prior to touchdown accurately (Wright et al., 2000). It was also found that individuals with an ankle muscle strength imbalance had a higher incidence of inversion ankle injury (Baumhauer et al., 1995).

The mechanism of a lateral ankle sprain involves excessive subtalar inversion and tibiotalar plantarflexion (Baumhauer et al., 1995). Using muscle-model driven computer simulations, Wright et al. examined the dependence of sprain occurrence on the foot positioning (Wright et al., 2000). An ankle sprain was said to have occurred when the torque about the subtalar joint exceeded a certain threshold value. The magnitude of this threshold value that would cause an injury varies between the subjects, so this value was determined by using a range of thresholds which resulted in maximum torques. Hence, the results varied based on the thresholds used. For larger inversion angle thresholds, a decrease in the initial plantarflexion angle caused a decrease in the sprain occurrence. Baumhauer et al. assessed the peak torque strength values for ankle plantarflexion and dorsiflexion for uninjured and injured subjects and found that the injured ankles had a higher mean plantarflexion peak torque when compared with the uninjured ankles (Baumhauer et al., 1995). For computer simulations of shuffle movements, increase in plantarflexion torques placed the ankle in a more plantarflexed and unstable position and therefore increased the risk of an inversion sprain (Wright et al., 2000). Beynnon et al. studied the risk factors associated with gender and observed that ankle injuries were related to increased calcaneal eversion range of motion (ROM) in females (Beynnon et al., 2001). Women with increased tibial varum and men with increased talar tilt were also more likely to sustain ankle injuries.

The force generating capacity of skeletal muscles depends on the speed of contraction, type of contraction, length of muscle fibers, and type of muscle fibers (Baumhauer et al., 1995). Beynnon et al. examined the muscle reaction time in female athletes and found contrasting observations (Beynnon et al., 2001). The authors found that females who had a previous ankle injury were at a higher risk for a recurrence, as their gastrocnemius muscle required less time to react while the tibialis anterior muscle required more time to react in response to a dorsiflexion perturbation. The delay in the reaction time of tibialis anterior reflects a deficit of the musculoskeletal system that may compromise the protective effect of the ankle muscle on ankle joint stability, thereby predisposing these female athletes to ankle sprain injuries (Beynnon et al., 2001). To study the effect of the peroneal muscles on inversion ankle sprains, Baumhauer and the co-authors measured ankle muscle concentric strength throughout its full range of motion in an open kinetic chain exercise with ankle in a subtalar neutral position. The authors showed that individuals with a muscle strength imbalance with an elevated eversion-to-inversion strength ratio (> 1.0) had a higher incidence of ankle inversion injury (Baumhauer et al., 1995).

INFLUENCE OF INVERSION STRESS ON ANKLE EMG

The main mechanisms of ankle sprains are from either contact or non-contact situations such as twisting, turning, collision, falling or tripping (Kofotolis and Kellis, 2007). To shed more light on the involvement of ankle/leg muscles during ankle sprains, researchers have studied electromyographic (EMG) behavior of ankle muscles during inversion stress (Lynch et al., 1996; Ebig et al., 1997; Cordova et al., 1998; Alt et al., 1999; Cordova and Ingersoll, 2003; Schmidt et al., 2005; Ty Hopkins et al., 2007; Kernozek et al., 2008). In an experimental set-up, a sudden inversion perturbation is introduced while a subject is standing on a tilt platform (a trap door platform) than can be tilted (inverted) to simulate the ankle sprain mechanism while EMG activity of leg muscles and kinematic data are recorded.

A trapdoor platform consists of a raised platform with a rotating surface that can be tilted to certain degrees (20 – 35°) to simulate inversion movement in ankle sprains (Lynch et al., 1996; Ebig et al., 1997; Cordova et al., 1998; Alt et al., 1999; Cordova and Ingersoll, 2003; Schmidt et al., 2005; Ty Hopkins et al., 2007; Kernozek et al., 2008). A release mechanism (rope, magnetic, or pneumatic device) of the tilting surface is normally used to initiate the inversion movement. Since the peroneal longus (PL) and tibialis anterior (TA) are the two respective major everters and inverters of the ankle, the EMG activity of PL, TA along with other ankle muscles is commonly collected using bipolar surface electrodes. The placement of EMG electrodes can be specified based upon some absolute or relative approaches. The study by Lynch et al., (Lynch et al., 1996) used the absolute approach, where the TA electrode was placed at the junction of the proximal and middle third of the tibia, and 1cm lateral to the subcutaneous border. The electrode for the PL was at the junction of the proximal and middle third of the fibula, over the palpable lateral compartment (Lynch et al., 1996). Other authors opted to use the relative approach, in which they align the electrodes with the direction of the muscle fibers over the most protuberant (middle) part of the muscle belly (Ebig et al., 1997).

EMG data can be analyzed in time as well as frequency domains. However, most EMG studies of ankle inversion stress analyze EMG data in the time domain. In the time domain, timings (e.g. onset, offset, duration, and latency) and magnitudes (mean EMG, and integrated EMG) can be analyzed from the collected EMG signals. Many studies use reaction times or latencies. For most latency calculations, the EMG data recorded from 250 ms before onset of tilting of the platform until 1 second after the inversion moment is sampled. Latency was defined as the time difference between the onset of the inversion platform tilting and the onset of the EMG activity 10 standard deviations above the baseline (Lynch et al., 1996; Kernozek et al., 2008). EMG activity can be integrated, often referred as integrated EMG (IEMG) and also used to examine the muscle effort (Alt et al., 1999; Hopper et al., 1999). Muscle activation duration is often identified for the purpose of IEMG calculation and can be defined as the duration of the time window after the start of rotation of the trap door up to 200 ms (Nieuwenhuijzen et al., 2002).

Another method to examine EMG magnitude is to use averages of normalized EMG signals. Isometric reference positions (IRPs) were recorded for PL and TA muscles in a study by McLoda et al (McLoda et al., 2004). During the data collection, 200 ms of muscle activity prior to heel strike was recorded. Then the onset and offset of muscle activity was identified interactively. The raw EMG signals were converted to linear envelopes by zeroing to the baseline, full-wave rectifying and low pass filtering the signal. The average values of the linear envelope were normalized to %IRP (McLoda et al., 2004).

Examining data after analysis, Hopkins et al. found that, the reaction times of PL and TA during inversion perturbation were 74 ms and 73 ms, respectively (Ty Hopkins et al., 2007). The effect of speed of plantarflexion is also shown to significantly influence the muscle latency response (reaction time) (Lynch et al., 1996). Lynch et al. studied the EMG latency changes of PL and TA muscles while subjecting the ankle to 20° plantarflexion at the rates of 50 and 200 °/s. Response of TA was significantly shorter (92 ms) from movement onset of 200 °/s of plantarflexion than (107 ms) 50 °/s. Similarly, the latency of PL was also significantly shorter at the faster speed (89 ms) than the slow speed (99 ms) (Lynch et al., 1996). Nieuwenhuijzen et al. observed two EMG responses in PL when the ankle is subjected to inversion (Nieuwenhuijzen et al., 2002). The first small response (M1) occurs about 40 ms after the start of the perturbation and has a duration of about 25 ms. The second and consistent response (M2) occurs about 100 ms after the inversion and has duration of about 35 ms (Nieuwenhuijzen et al., 2002).

LANDING MOVEMENT AND EMG ACTIVITY OF THE ANKLE

The amount of the lower leg muscle pre-activity in preparation for foot contact is potentially useful information for investigating the ankle musculature restraint mechanism while subjected to a sprain simulation (McLoda et al., 2004). Santello et al. evaluated the timing and amplitude of TA and soleus (SOL) muscles in jump landing movements from five different heights (Santello and McDonagh, 1998). The raw EMG signal recorded during the period between take-off and touch-down was full wave rectified and a continuous integration of all the data points was performed. The IEMG and the fall time were then normalized to 100 percent. The slope of the normalized IEMG is dependent on the rate of increase of the EMG signal. The normalized IEMG trace was then compared to a reference line with slope equal to 1, representing the relationship between the normalized IEMG and the normalized time. The EMG onset latency was defined as the point in time when the distance between the normalized IEMG slope and the reference line was the greatest, which is a point when the slope of the normalized IEMG line started to increase continuously, thus, indicating the onset of a continuous build-up of muscle activity. The authors found preparatory EMG activity in the TA and SOL muscles prior to the impact of landing. At 100 ms prior to touchdown, a gradual increase in activity was seen, when co-activation of both muscles occurs. Funase et al. (Funase et al., 2001) also observed that the MG activity began about 100 ms before landing (Funase et al., 2001).

Fu et al. examined the pre-landing ankle muscle responses using a co-contraction index (Fu and Hui-Chan, 2007). A Co-contraction index between TA and MG (TA/MG CoI) was defined as the ratio of twice the antagonist (TA or MG) activity to total agonist and antagonist (TA and MG). This can be expressed as $\frac{2(TA\ or\ MG)}{TA+MG}$. Muscle activities in TA and MG were normalized with respect to the peak ensemble EMG amplitude of their corresponding muscles in the unexpected drop landings. It was observed that those who had a greater TA/MG CoI were found to experience a greater magnitude of impact force on landing. Also, subjects who had greater errors in ankle repositioning co-contracted their ankle dorsiflexor and plantarflexor to a greater extent in preparation for landing. The clinical relevance of this study is that the modulation of the ankle agonist-antagonist muscle pair could increase the ankle stiffness in these subjects, thereby enhancing the stability of the ankle joint in preparation during jumping and landing movements (Fu and Hui-Chan, 2007).

Santello et al. found certain modulations of the soleus and tibialis anterior muscles associated with landing height (Santello and McDonagh, 1998). The author observed that after touchdown, both TA and SOL muscles are active throughout dorsiflexion, after which EMG activity slowly decreases. The post landing EMG amplitude of SOL and TA significantly increased as the landing height increased from 0.2, 0.4, 0.6, 0.8 to 1 m (Santello and McDonagh, 1998) and the finding is analogous to the significant increase in activation of the gastrocnemius and soleus muscles 100 ms prior to ground contact with increasing drop heights from 50% to 120% of optimal drop height (Sousa et al., 2007). Drop jumps from 120% of an optimal drop height had higher averaged EMG of gastrocnemius and soleus compared to drop jumps from 50%. These findings are also supported by Hoffren et al. who also observed that gastrocnemius pre-activity increased with increasing drop height (Hoffren et al., 2007). Arampatzis conducted a detailed study on the effect of landing height on the MG, TA and PL muscles during landing from height of 1.0, 1.5 and 2.0 m (Arampatzis et al., 2003). The EMG signals were recorded at 1000 Hz sampling frequency, after which the EMG was rectified and smoothed using second-order Butterworth low-pass filter with a cut-off frequency of 10Hz. The subsequent linear envelope EMG data were normalized by:

$$EMG_{Nk} = \frac{\mathbf{EMG_{Fk}}}{\mathbf{EMG_{max,k}}} * \mathbf{100}$$

Where EMG_{Nk} is defined as the normalized EMG-data of k_{th} muscle, EMG_{Fk} is the linear enveloped EMG from k_{th} muscle, $\mathbf{EMG_{max,k}}$ is the maximum linear envelope EMG from k_{th}muscle , during the landing from 1.0 m. From the normalized EMG data, pre-activation time ($\mathbf{PA_{time}}$) was defined from onset of muscle activity until touchdown and $\mathbf{IEMG_{PA}}$ was calculated as the integral of the pre-activation phase. The integral of the landing phase $\mathbf{IEMG_{LA}}$ was estimated from touchdown until 300 ms after touchdown and the maximum of the EMG-activity was defined as EMG_{max}. The results showed that the IEMG during pre-activation phase and landing phase, and EMG_{max} all show significantly higher values for all muscles when landing from 2 m, than from 1 m. Both TA and PL demonstrated activity before touchdown and reach their maximal activity about 150ms after ground contact. Hence the author argues that as the landing height increases, the higher muscle activity before and after touchdown, around the ankle improves the stability of the talocrural joint (Arampatzis et al., 2003).

Investigation of ankle muscle activity when subjected to inversion perturbation while landing could provide more insight into the mechanism of ankle inversion sprains in sports such as basketball. Nieuwenhuijzen et al. (Nieuwenhuijzen et al., 2002) and Gruneberg et al. (Gruneberg et al., 2003) studied the EMG activity of PL, TA and MG muscles while an inversion perturbation was induced at the ankle using a trapdoor platform during step-off landing from a height of 30 cm. The step-off landing was performed by having the left foot positioned slightly forward and then pushing off with an almost straight right leg. The landing surface consisted of the trap door for the left foot and a solid box of same dimensions and material for the right foot.

Both the authors (Nieuwenhuijzen et al., 2002; Gruneberg et al., 2003) sampled the EMG signals at 500Hz frequency, which may not be adequate, compared to the 2000 Hz used by other researchers (Santello and McDonagh, 1998; Duncan and McDonagh, 2000).

While analyzing the data, Nieuwenhuijzen et al. (Nieuwenhuijzen et al., 2002) and Gruneberg et al. (Gruneberg et al., 2003) used similar approaches. The mean EMG activity was calculated between the beginning and the end of the muscle response. A time window was determined from appropriate responses by visual judgment on the average EMG data obtained for each subject to quantify the amplitudes of the responses. The response latency and duration were calculated based on the onset of response and duration of the time window. The inspection of the data revealed two facilitatory responses following landing impact, which were termed short latency (SLR) and long latency (LLR) responses (Gruneberg et al., 2003) which were similar to the findings of Nieuwenhuijzen et al. who observed two EMG bursts (responses), a small early but inconsistent burst, M1 and a larger and more consistent one, M2. The mean M1 latency was 41 ms with a mean duration of 18 ms (Nieuwenhuijzen et al., 2002). The M2 response exhibited a mean latency of 87 ms and a mean duration of 27 ms. However, the M1 was visible in only 17% and the M2 in 61% of all the trials. Gruneberg et al. observed that the response amplitude of PL was significantly less in the non-inverting condition than in the inverting condition, while TA did not show significant differences (Gruneberg et al., 2003). The results from this study demonstrate that the sudden ankle inversion can be reproduced in laboratory settings (Nieuwenhuijzen et al., 2002). As there have not been many studies focusing on EMG activity while landing on combined perturbation of inversion and plantarflexion, more research is warranted to determine the mechanism of lateral ankle sprains.

SUMMARY

The review of the literature indicates that the lateral ankle sprain is the most common non-contact injury among athletes (Garrick, 1977; Fong et al., 2007; Hootman et al., 2007; Kofotolis and Kellis, 2007). The factors causing ankle sprains depend on foot positioning, muscular strength and neuromuscular reaction time of the ankle muscles (Baumhauer et al., 1995; Wright et al., 2000; Beynnon et al., 2001). Ankle sprains occur mostly as a result of inversion of the foot, so the adaptation technique of the ankle muscles to sudden inversion has been studied in the literature (Lynch et al., 1996; Ebig et al., 1997; Cordova et al., 1998; Alt et al., 1999; Cordova and Ingersoll, 2003; Schmidt et al., 2005; Ty Hopkins et al., 2007; Kernozek et al., 2008). The speed of inversion plays a major factor in the EMG activity of the muscles (Lynch et al., 1996). Limited studies have been conducted to examine the effects of the landing movement on the ankle muscles. The landing height has been shown to influence the EMG activity of the muscles. With increased landing height, the muscles experience increased EMG activity to help stabilize the joint during landing (Santello and McDonagh, 1998; Duncan and McDonagh, 2000; Arampatzis et al., 2003; Hoffren et al., 2007; Sousa et al., 2007). There has been limited research on the effects of landing on combined inversion and plantarflexion on the ankle muscles.

CHAPTER III

METHODS

SUBJECTS

Twelve healthy adults from the University of Tennessee student population were recruited as subjects for this study. The participants were healthy and did not suffer from any previous lateral ankle sprains or multiple ankle sprains within the period of at least six months. Each subject attended one session of the experiment, which was approximately ninety minutes. The testing session took place at the Biomechanics/Sports Medicine Laboratory at the University of Tennessee. The experiment procedure was explained to the subject along with the benefits and risks of the study. The informed consent form along with the experimental protocol approved by the University of Tennessee Institutional Review Board was read and signed by the subject prior to any testing.

INSTRUMENTATION

Anthropometric measures

The body mass in kilograms (kg) and the height in meters (m) of the participants were measured using a calibrated physician's scale.

Motion Analysis system

A seven-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was used to obtain the three dimensional kinematics of the right ankle during the testing. Reflective anatomical and tracking markers were attached on both the legs of the subject during the testing. The anatomical markers placed on the following locations bilaterally: iliac crests, greater trochanters, lateral and medial femoral epicondyles, lateral and medial malleoli, lateral, medial, distal and proximal heels, and the fifth and first metatarsal heads. A cluster of 4 tracking markers was placed on the right and left shank and thighs. A cluster of 2 tracking markers were also placed above the iliac crests on both right and left sides.

Electromyographic measurements

An 8-channel surface electromyography system (2400 Hz, Noraxon USA, Inc., Scottsdale, AZ, USA) was used to monitor the medial gastrocnemius, peroneal longus and tibialis anterior muscles of the right leg. Disposable self-adhesive Ag/AgCl bipolar surface electrodes were placed on the middle portion of the respective muscles. The ground electrode was placed on the head of fibula.

Inversion/Plantarflexion platform

A customized trapdoor platform was used to initiate a 25° inversion movement or a combined 25° inversion and 25° plantarflexion movement for the right foot in landing during the testing session (Figure 1). The platform consisted of a movable flap that was help by a ball hinge, and fall on impact. Thus, creating the tilted surfaces based on the tilt on the wooden blocks placed underneath the flap. A flat platform of 16 inches was used on the left side. The subjects landed on the trapdoor platform with the right foot and the left flat platform with the left foot.

EXPERIMENTAL PROTOCOL

The subjects were required to attend a single session of about 90 minutes in the Biomechanics/Sports Medicine Laboratory at the University of Tennessee. The anthropometric data were measured from the participant using the calibrated physician’s scale. The subject was provided with the standard lab shoes (running). The subject then performed a standard warm-up running on the treadmill at 3.4 miles/hr for 4-5 minutes and stretching.

After the warm-up, the subject performed practice drop landings from 30 cm on the three platforms, to get accustomed to the drop landing style. The EMG electrodes were then placed on the mid section of peroneal longus (PL), tibialis anterior (TA) and the medial gastrocnemius (MG) muscles by the relative placement method using palpation of the muscles. Three Maximum Voluntary Isometric Contraction (MVIC) trials of the three muscles were measured individually for each of the three muscles. The MVIC measurements were taken while the subject was in the standing position. For PL, the subject everted the ankle against a manual resistance applied by the primary investigator. For TA, the subject maximally dorsiflexed the ankle joint against a manual resistance applied by the same investigator. For MG, the subject plantarflexed the ankle against a downward manual resistance applied from the shoulders.

After the MVIC trials were completed, the anatomical and tracking reflective markers were placed on the subject. The static trials were recorded with the anatomical and tracking markers placed on the subject, while they stood still on the flat platforms. The dynamic trials were recorded with only the tracking markers on the subject. During the dynamic trials, the subjects performed self-initiated drop landings from the overhead bar 0.30 m above the trapdoor landing platform, measured from the height of the mid-heel of the subject to the center of the contact surface. The height of the overhead bar was adjusted using an electrical hoist. The study had three drop landing movement conditions: landing onto a flat surface, a 25° inverted surface, and a combined tilted surface of 25° inversion and 25° plantarflexion. The subject performed five successful trials in each of the three conditions. The subject was asked to perform the landing naturally and avoid stiff (too little knee bending) and soft (too much knee bending) landing. Landing on the combined tilted surface without practice lead subjects to lose balance and fall after landing, hence the surface conditions were not randomized for the purpose of safety. The subjects were asked to land the left foot on the flat surface and the right foot on the trapdoor platform. A successful trial was when the subjects landed naturally on the platform and were able to maintain balance after landing. Any unsuccessful trial was repeated.

DATA AND STATISTICAL ANALYSIS

The EMG and kinematic data were analyzed using the Visual3D biomechanics analysis suite (4.0, C-Motion, Inc., Germantown, MD). The raw EMG signals were first filtered by a band-pass filter with 25 Hz high-pass and 450 Hz low-pass cutoff frequencies (Merletti, 1999). A root mean square (RMS) with a 60 ms window was then applied to the EMG signals to the rectified MVIC and movement EMG signals. The movement EMG signals were then normalized the maximum of the respective MVIC trials .The onset of the tested muscles were identified by using the 10 standard-deviation criterion (Kernozek et al., 2008) and adjusted interactively in Visual3D. The linear enveloped EMG signals were then integrated from the landing contact to 350ms to obtain the integrated EMG (IEMG).

The muscle latencies were expressed as the time period between ground contact and onset of muscle activity. The kinematic variables of the right ankle were computed using Visual 3D, and their critical events and values were determined by a customized computer program (VB_V3D, MS VisualBasic 6.0). The variables of interest were contact sagittal ankle angle, peak sagittal ankle angle, contact ankle inversion angle, peak frontal plane angle, peak ankle inversion velocity and peak ankle transverse angle (Table1) The onset of the landing phase was determined by the start of vertical ground reaction force for the flat surface condition. For the two tilting surfaces, calculating the time frame in which the velocity of the markers placed on the movable testing platform was zero was defined as the onset of landing phase. The drop landing movement was analyzed from the foot contact to 350 ms after foot contact. The 3D kinematic angles were defined by the right-hand rule in Visual3D and followed a Cardan X-Y-Z rotation sequence. The ankle dorsiflexion, inversion, internal rotation angles and velocities are positive.

The analysis of the kinematic data produced 27 variables. To narrow down the number of variables to the ones that are not highly correlated and biomechanically meaningful about the ankle movement, a principal component analysis was performed. This method of analysis identifies the variables that are highly correlated with each other. It seeks a linear combination of variables such that the maximum variance is extracted from the variables. It then removes this variance and seeks a second linear combination, which explains the maximum proportion of the remaining variance. The kinematic variables selected for further analyses were uncorrelated ones based on the principal component analysis and biomechanical significance related to ankle movements (Table 1). The component loadings are the correlation coefficients between the variables (rows) and factors (columns). The squared component loading is the percent of variance in that variable explained by the factor. For the variables, whose loadings are higher than 0.7, it confirms that the variables are represented by a particular factor.

A 3 × 3 (Muscle × Surface) repeated measures analysis of variance (ANOVA) was conducted on IEMG and latency of the muscles to examine the effect of the surface on each of the muscles, with an alpha level of 0.05 (SPSS 15.0, SPSS Inc., Chicago, IL). For analyzing the effect of the surface on the kinematic variables, one-way repeated measures ANOVA was conducted across the three surface conditions. Post hoc comparisons were conducted to detect specific differences among the surfaces with a Bonferroni procedure to adjust the significant level to $p < 0.0166$ for multiple comparisons.

CHAPTER IV

EFFECT OF TILTED SURFACES ON ANKLE KINEMATICS AND EMG ACTIVITIES IN LANDING

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INTRODUCTION

Ankle sprains are the most predominant injury in sports (Fong et al., 2007; Hootman et al., 2007), with the highest injury rates reported in football and basketball at 1.34 per 1000 athlete exposures (Hootman et al., 2007). These data were supported by high ankle sprain prevalence rates at 76.7% reported by Fong et al. (Fong et al., 2007), 64% reported by Kofotolis and Kellis (Kofotolis and Kellis, 2007), and 73.5% reported by Yeung et al. (Yeung et al., 1994). Post- injury symptoms include pain, weakness, crepitus, instability, swelling, and stiffness. Ankle sprains not only hinder athletic performance but also cause missed participation (Yeung et al., 1994). In sports, ankle sprains can occur by contact or non-contact mechanisms (Garrick, 1977). About 77% of non-contact ankle sprains take place during landing or cutting movements (Kofotolis and Kellis, 2007).

Some researchers have noted that neuromuscular strength and reaction time of the ankle muscles appear to influence the occurrence of sprains (Baumhauer et al., 1995; Beynnon et al., 2001). The muscle activity of the lower extremities such as medial gastrocnemius (MG), peroneus longus (PL), and tibialis anterior (TA) can affect the positioning of the ankle, stabilize the joints, and restrict the maximal motion by means of higher activation levels before and after touchdown (Arampatzis et al., 2003). As the typical mechanism of a lateral ankle sprain includes excessive inversion when the ankle is plantarflexed (Garrick, 1977), many studies have examined ankle muscle adaptations to inversion stress in the literature (Lynch et al., 1996; Ebig et al., 1997; Cordova et al., 1998; Alt et al., 1999; Cordova and Ingersoll, 2003; Schmidt et al., 2005; Ty Hopkins et al., 2007; Kernozek et al., 2008). There has been limited research subjecting the ankle to a combined stress of inversion and plantarflexion (Ebig et al., 1997; Duncan and McDonagh, 2000). Ebig et al. (Ebig et al., 1997) subjected the ankle to a combination of inversion and plantarflexion of 20° and observed a response time of 65 ms for PL and 71 ms in TA. Investigation of the ankle muscle activity when subjected to inversion perturbation during landing could provide more realistic situations simulating a lateral ankle sprain compared to the inversion trap-door testing protocol (Zhang et al., 2009). Also, Lynch et.al., (Lynch et al., 1996) reported that the speed of inversion affects the muscle activity, and Nieuwenhuijezen et.al., (Nieuwenhuijzen et al., 2002) demonstrated that jumping on tilting surfaces provide higher tilting velocities (595 deg/s) than walking on tilting surfaces (403 deg/s).

Nieuwenhuijzen et al. (Nieuwenhuijzen et al., 2002) and Gruneberg et al. (Gruneberg et al., 2003) studied the EMG activity of PL, TA and MG muscles while an inversion perturbation was induced at the ankle using a trapdoor platform during step-off landing. Gruneberg et al. (Gruneberg et al., 2003) observed that the response amplitude of PL was significantly less in the flat condition than in the inverting condition, while TA and MG did not show significant differences. The landing height has also been shown to influence the EMG activity of the muscles (Santello and McDonagh, 1998; Duncan and McDonagh, 2000; Arampatzis et al., 2003; Hoffren et al., 2007; Sousa et al., 2007). While landing on flat surfaces, increasing the landing height elicits MG, PL and TA muscles to be more active to help stabilize the joint during landing.

Therefore, the purpose of this study was to examine effects of landing surface inclination conditions (flat, inversion alone, a combination of inversion and plantarflexion) on the EMG activity of PL, MG and TA muscles and ankle kinematics during a drop landing movement. The hypotheses tested in this study were that increased MG, PL and TA muscle activities would be observed in landing on the combined tilted surface compared to the flat and inverted surfaces, and similar inversion but greater plantarflexion would be seen in the combined tilting surface compared to the inverted surface.

METHODS

Participants

Twelve healthy recreational athletes (mean ± SD age: 24.4 ± 4.2 years, height: 1.74 ± 0.09 m, mass: 71.4 ± 11.6 kg), ten males and two females, participated in this study. Participants did not have a history of major lower extremity injury, and did not suffer from a lateral ankle sprain within 6 months prior to testing. The informed consent form and the study protocol were approved by the Institutional Review Board of the University of Tennessee, Knoxville, and was signed by the participants.

Instrumentation

A seven-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was used to obtain the three dimensional (3D) kinematics during the testing. Anatomical markers, used to define the anatomical segments, were placed on the right and left iliac crests and greater trochanters and the lateral and medial sides of the epicondyles and malleoli. They were also placed on the proximal and superior heel, lateral 5th metatarsal and medial 1st metatarsal bone surfaces of the right leg. An 8-channel surface electromyography system (2400 Hz, Noraxon USA, Inc., Scottsdale, AZ, USA) was used to collect EMG data from MG, PL and TA muscles of the right leg. Disposable self-adhesive Ag/AgCl bipolar surface electrodes were placed on the middle portion of the respective muscles with an inter-electrode distance of 2 cm. The skin of the electrode attachment sites was shaved, gently abraded and cleaned before the application of the electrodes. The ground electrode was placed on the head of fibula.

A customized trapdoor landing platform was used to initiate a 25° inversion tilt or a combined 25° inversion and 25° plantarflexion tilt for the right foot in landing during the testing session (Figure 1). The platform consisted of a movable flap that was held by a ball hinge, and would fall on impact. Thus, creating the tilted surfaces based on the tilt of the wooden blocks placed underneath the flap. A flat platform was used on the left side for the left leg.

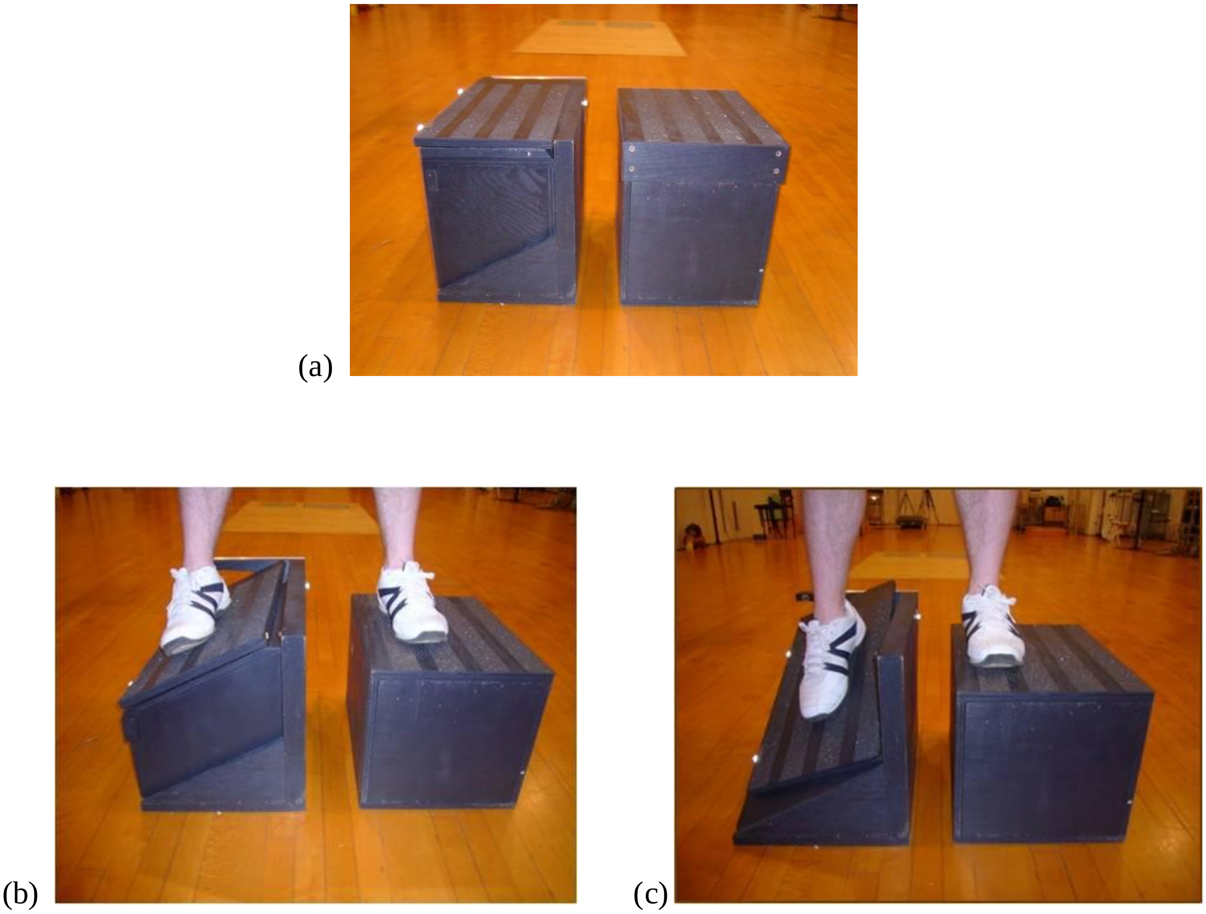

Figure 1. Landing platforms (a) flat, (b) 25°inversion and (c) 25° inversion + 25° plantarflexion surface.

Experimental Protocol

The subjects began the testing with a warm up of treadmill running for five minutes. The subjects were then asked to perform practice landings, to get accustomed to the platforms. After the warm up, the EMG electrodes were placed on the muscles. Three maximum voluntary isometric contractions (MVIC) of the three muscles were then measured individually while the subject was in the standing position. For PL, the subject everted the ankle against a manual resistance applied in the opposite direction by the primary investigator. For TA, the subject maximally dorsiflexed the ankle joint against a manual resistance applied in the opposite direction by the same investigator. For MG, the subject stood on their toes against a downward manual resistance applied from the shoulders. The subjects then performed self initiated drop landings from an overhead bar of 30 cm above the trapdoor platform with the right and left foot landing on the trapdoor and flat platforms, respectively. Each subject performed five successful landing trials on a flat surface (control), a surface with 25° inversion, a surface with combined 25° inversion and 25° plantarflexion. Landing on the combined tilted surface without practice lead subjects to lose balance and fall after landing, hence the surface conditions were not randomized for the purpose of safety. A successful trial was a trial where the subject was able to keep balance after landing on the surfaces.

Data and Statistical Analysis

The EMG and kinematic data were analyzed using the Visual3D biomechanics analysis suite (4.0, C-Motion, Inc., Germantown, MD). The raw EMG signals were first filtered by a band-pass filter with 25 Hz high-pass and 450 Hz low-pass cutoff frequencies (Merletti, 1999). A root mean square (RMS) with a 60 ms window was then applied to the EMG signals to the rectified MVIC and movement EMG signals. The movement EMG signals were then normalized the maximum of the respective MVIC trials .The onset of the tested muscles were identified by using the 10 standard-deviation criterion (Kernozek et al., 2008) and adjusted interactively in Visual3D. The linear enveloped EMG signals were then integrated from the landing contact to 350ms to obtain the integrated EMG (IEMG).

The kinematic variables of the right ankle were computed using Visual3D, and critical events and values were determined by a customized computer program (VB_V3D, MS VisualBasic 6.0). The analysis of the kinematic data produced 27 variables. To narrow down the number of variables to the ones that are not highly correlated and biomechanically meaningful about the ankle movement, a principal component analysis was performed. This method of analysis identifies the variables that are highly correlated with each other. The kinematic variables selected for further analyses were uncorrelated ones based on the principal component analysis and biomechanical significance related to ankle movements (Table 1). The dependent variables of interest included the contact sagittal ankle angle, peak sagittal ankle angle, contact ankle inversion angle, peak frontal plane angle, peak ankle inversion velocity and peak ankle transverse angle (Table 1).

The onset of the landing phase was determined by the vertical ground reaction force for the flat surface condition. For the two tilting surfaces, calculating the time frame in which the velocity of the markers placed on the movable testing platform was zero was defined as the onset of landing phase. Latency was defined as the period between the onset of muscle activity and onset of the landing phase. The drop landing movement was analyzed from the foot contact to 350 ms after foot contact. The 3D kinematic angles and moments were defined by the right-hand rule in Visual3D and followed a Cardan X-Y-Z rotation sequence. The ankle dorsiflexion, inversion, internal rotation angles and velocities are positive.

Table 1. Description of the kinematic dependent variables

Variable	**Description**
Cont_Sagittal	Contact Sagittal ankle angle
Max_Sagittal	Peak Sagittal ankle angle
Cont_Inv	Contact Inversion angle
Max_Front	Peak frontal plane angle
Max_Inv Vel	Peak inversion velocity
Max_Trans	Peak Transverse ankle angle

A 3×3 (surface × muscle) repeated measures analysis of variance (ANOVA) was conducted on the IEMG and latency of the muscles to examine the effect of the surface on each of the muscles, with an alpha level of 0.05 (SPSS 15.0, SPSS Inc., Chicago, IL). For analyzing the effect of the surface on the kinematic variables, one-way repeated measures ANOVA was conducted across the three surface conditions. Post hoc comparisons were conducted to detect specific differences among the surfaces with a Bonferroni procedure to adjust the significant level to $p < 0.0167$ for multiple comparisons.

RESULTS

Electromyographic Data

The ankle muscles displayed significant muscle × surface interaction among the three muscles and three landing surfaces in IEMG (F (4, 7) = 14.98, p = 0.002). The post hoc comparisons of individual muscles across surface conditions showed that the IEMG of MG (F (2, 9) = 18.79, p = 0.001) was significantly higher while landing on the combined surface than the flat surface and the inverted surface (Table 2). The IEMG of PL was similar across the landing surfaces. Furthermore the IEMG of TA (F (2, 9) = 10.86, p = 0.004) was significantly high while landing on the flat surface as compared to the tilted surfaces (Table 2). The latency of the muscles was expressed as the time between the onset of movement and the onset of muscle activity. For MG, the mean latency was -0.11 ms, -0.12 ms and -0.14 ms, for the flat surface, inverted surface and combined surface respectively. The mean latency of PL was 0.08 ms, -0.07 ms, and -0.10 ms, for the flat surface, inverted surface and combined surface respectively. Finally, the mean latency of TA was -0.04 ms, -0.05 ms and -0.12 ms, for the three respective surface conditions. The repeated measures ANOVA did not show significant differences in the latency of the muscles among the three landing surfaces. Representative normalized EMG curves were presented in Figure 2.

Table 2. Mean IEMG of the ankle muscles: mean ± STD.

Condition/ Muscle*	**Flat**	**Inverted**	**Combined**
Medial Gastrocnemius (%·s)	6.53±2.64 ^{c}	5.66±2.59 ^{c}	10.79±5.14
Peroneal Longus (%·s)	10.78±5.69	9.03±4.91	12.04±5.58
Tibialis Anterior (%·s)	20.45±5.65^{b,c}	14.45±5.53	11.54±4.36

Note: *: significant interaction between muscle and condition (p<0.05), ^{a} : significantly different from flat surface (p< 0.0166), ^{b}: significantly different from the inverted surface (p< 0.0166), ^{c}: significantly different from the combined surface (p< 0.0166).

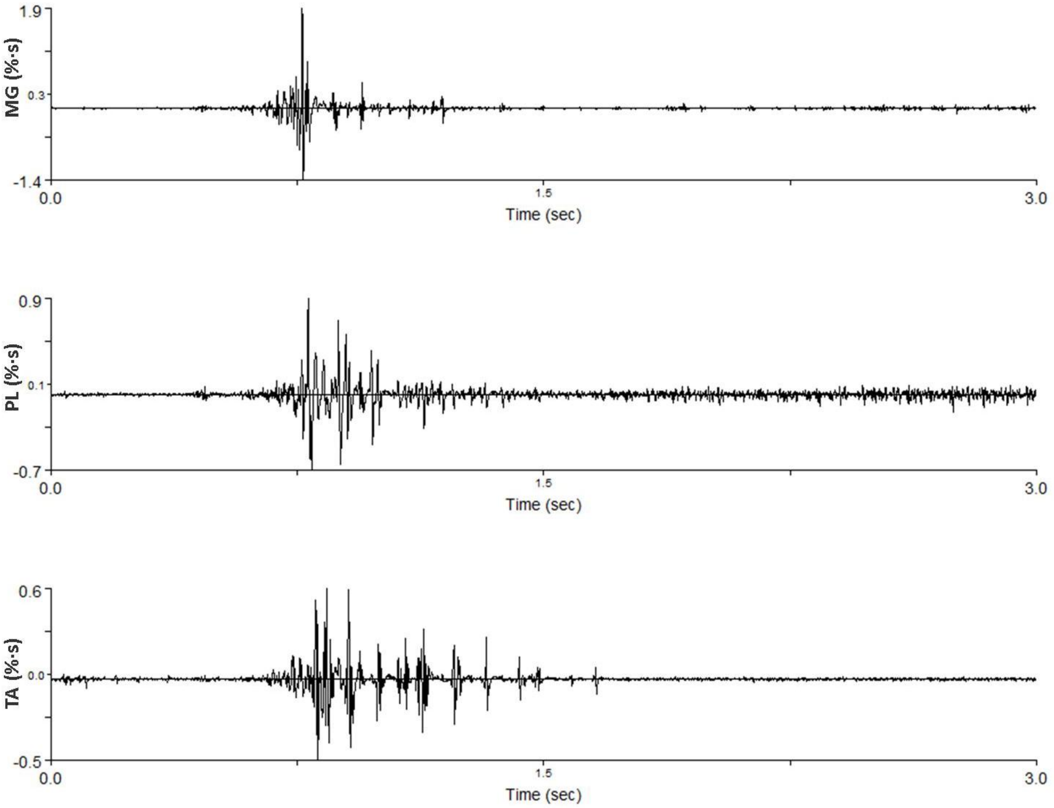

Figure 2. Representative normalized EMG signals of MG, PL and TA muscles while landing on the combined landing platform.

Kinematic Data

Representative ensemble curves of the ankle angles for the three surface conditions were presented in Figure 3. In the frontal plane, the ANOVA results showed a significant difference for the ankle contact angle (F (2, 10) = 51.75, p = 0.001) and peak frontal-plane angle (F (2, 10) = 974.73, p = 0.001). The post hoc comparisons indicated that both variables were significantly lower while landing on the flat surface than the inverted surface (Table 3). The peak inversion velocity (F (2, 10) = 119.20, p = 0.001) was significantly lower while landing on the flat surface than both the inverted surface and the combined surface (Table 3). In the transverse plane, the peak ankle angle (F (2, 10) = 82.46, p = 0.001) was significantly lower while landing on the flat surface than on the two tilted surfaces (Table 3).

In the sagittal plane, the ankle contact angle (F (2, 10) = 72.71, p = 0.001) while landing on the inverted surface was significantly higher (dorsiflexion) than the flat and combined surface (plantarflexion) (Table 3). The peak sagittal plane angle (F (2, 10) = 596.53, p = 0.001) was significantly greater while landing on the flat surface than the inverted and combined surface (Table 3). In addition, the peak dorsiflexion angle while landing on the inverted surface was significantly greater than that on the combined surface.

Table 3. Mean kinematics of the Ankle: mean ± STD

Condition	**Flat**	**Inverted**	**Combined**
Cont_Sagittal (deg)	-9.2±2.6 [b]	3.3±1.7 [c]	-13.1±1.2
Max_Sagittal (deg)	26.8±2.1[b,c]	13.1±2.2 [c]	-11.4±1.6
Cont_Inv (deg)	1.9±1.3 [b,c]	14.9±1.0 [c]	5.4±1.2
Max_Front (deg)	-1.5±1.1 [b,c]	28.1±1.0 [c]	23.0±1.7
Max_Inv Vel (deg/s)	31.2±12.3 [b,c]	520.6±67.6	517.0±29.2
Max_Trans (deg)	-8.9±1.0 [b,c]	7.3±1.0	7.7±1.6

Note: [a] : significantly different from flat surface (p< 0.0166), [b]: significantly different from the inverted surface (p< 0.0166), [c]: significantly different from the combined surface (p< 0.0166).

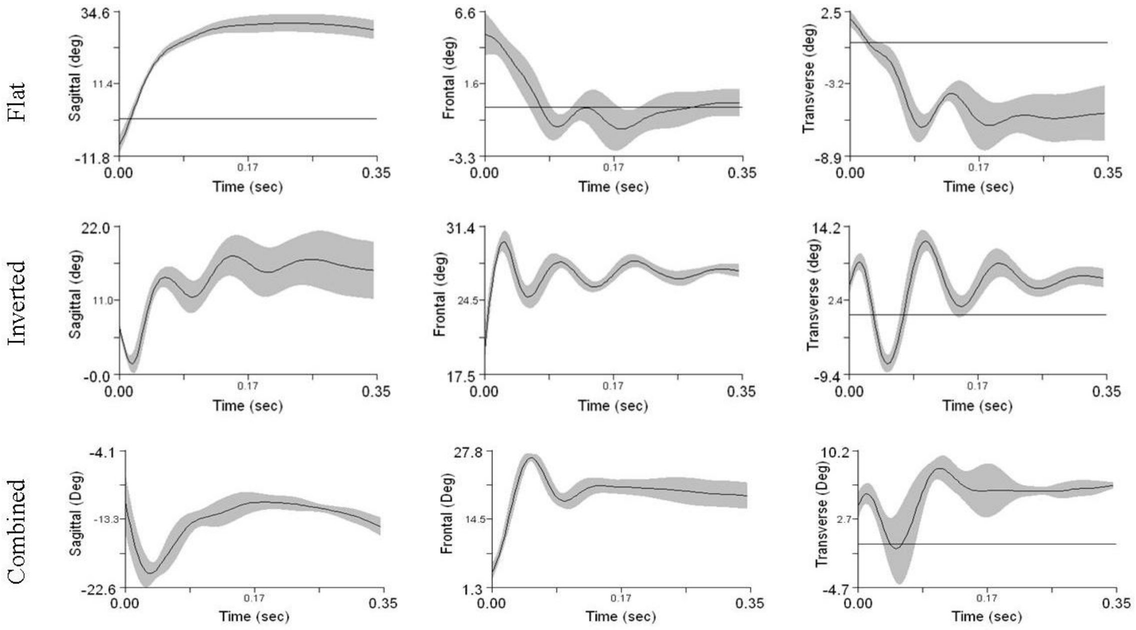

Figure 3. Representative ensemble curves of ankle angles across the flat, inverted and combined landing surfaces.

DISCUSSION

Comparison between landing on flat surface and tilted surfaces

This study was conducted to examine the ankle muscle EMG activity and kinematics when subjected to an inversion perturbation and a combination of inversion and plantarflexion perturbation in drop landing. The current study found no significant differences among the onset latency of the muscles across the three landing surfaces which is similar to the findings of Gruneberg et.al., who conducted landing trials on inverted surfaces (Gruneberg et al., 2003).

This study also depicts a significant interaction between the muscles and surfaces with MG showing similar patterns in the flat and inverted surfaces but increased activity in the combined surface, and TA demonstrating significantly higher activity in the flat surface than the two tilted surfaces. TA and MG muscles being dorsiflexor and plantarflexor respectively, behave like agonist- antagonist muscle pair in stabilizing the ankle joint in dynamic movements (Fu and Hui-Chan, 2007). MG demonstrates a significant increase in activity while TA demonstrates a significant decrease in activity from landing on the flat surface to the combined surface. Thus, this study concurs with previous literature on the behavior pattern of muscle activity. Across the three muscles during the flat surface landing, TA demonstrates the highest muscle activity (20.45%·s) followed by PL (10.78%·s) and MG (6.53%·s). This muscle activity order was supported by the findings by Arampatzis et.al. who also found similar muscle behaviors, with IEMG values in landing from a 1 m height being 17.24 %·s, 14.78 %·s and 10.41 %·s for TA, PL and MG respectively (Arampatzis et al., 2003). In the current study, the ankle kinematics exhibited significant differences while landing on flat compared to tilted surfaces. The flat surface induced high dorsiflexion of the ankle (26.8°), however the combined surface induced plantarflexion (-11.4°). The EMG findings supported the kinematic results with significant higher IEMG of MG while landing on the combined surface than the flat surface. The combined tilted surface in this study successfully induced a high degree of plantarflexion as it stimulated the major plantarflexor to produce high muscle activity.

For the contact and peak angle of the ankle in the sagittal plane, landing on the flat surface causes a large range of motion (ROM) of dorsiflexion (36.0°, Table 3) and thus induces high activity of TA, whose main function is to stabilize the ankle during the dorsiflexion. The dorsiflexion ROM of the ankle is much smaller while landing on the inverted surface (9.8°), and is almost none existent in landing on the combined surface (1.7°, Table 3). These results are supported by significantly higher TA muscle activity in the flat surface landing than the tilted surfaces.

Kawakami et.al. (Kawakami et al., 2002) studied MG muscle fascicle behavior during maximal plantarflexion movement of the ankle, with and without countermovement. During the plantarflexion without countermovement, the fascicle length continuously decreased during the exercise, resulting in higher EMG activity, which is similar to the movement of the ankle while landing on the combined tilted surface in the current study, as the platform induces plantarflexion of the ankle. Kawakami et.al. also found that during the ankle countermovement plantarflexion, MG fascicle length increased at the onset of dorsiflexion and remained constant as the ankle was dorsiflexed and the muscle was under eccentric contraction, and finally decreased as the ankle plantarflexed (Kawakami et al., 2002). In this study, the ankle undergoes dorsiflexion while landing on the flat surface, as the contact angle is plantarflexion (-9.2°) whereas the peak sagittal angle is dorsiflexion (26.8°). Thus, the low EMG activity of MG while landing on the flat surface may be explained by the increase in fascicle length at the onset of dorsiflexion accompanied by less EMG activity.

The increase in MG activity in the combined surface landing compared to the flat surface landing may be due to shortened muscle fascicles and elongated tendinous tissue during eccentric contraction of the muscle. The behavior of MG fascicles and tendon tissue during landing were examined in the studies by Sousa et.al. (Sousa et al., 2007) and Hoffren et.al. (Hoffren et al., 2007) during sledge drop jumps. Sousa et. al. (Sousa et al., 2007) observed that increase in landing height of drop jumps (50 – 120% of an optimal drop height) on a sledge causes an increase in stretch amplitudes of MG muscle-tendon unit complex . The MG fascicles were shortened while the tendinous tissue length increased with increasing drop heights. These changes were coupled with increasing EMG activity (Hoffren et al., 2007; Sousa et al., 2007). Although the landing height was not increased in the current study, the MG activity findings are supported by the above-cited literature.

In the frontal plane, the tilted surfaces induce a significantly higher amount of inversion than the flat surface. The contact inversion angle is 14.9° in the inverted surface, while it is 1.9° in the flat surface landing. Similarly, the inverted surface induces a peak inversion angle of 28.1°, whereas the peak frontal plane angle induced by the flat surface is eversion (-1.5°). Also, the inverted and combined surfaces induce significantly higher inversion velocities (520.6 °/s and 517°/s respectively) compared to the flat surface (31.2°/s). Thus, it can be seen that the ankle undergoes a larger range of motion while landing on the inverted surface (13.2°) compared to the flat surface (-3.4°). However, no significant difference of PL's IEMG between the two conditions were observed, as, landing on the flat surface (10.78 %·s) is similar to that of the inverted surface (9.03 %·s). Future studies are required to shed more light on the causes of this behavior of PL.

Comparison between landing on inverted and combined surfaces

Most ankle sprain studies have mainly concentrated on inversion perturbations. However, plantarflexion is also known to cause high risk of lateral ankle sprain (Wright et al., 2000). Wright et.al., (Wright et al., 2000) defined an ankle sprain to occur when the torque about the subtalar joint exceeded a certain threshold. For larger torque, a decrease in the initial plantarflexion angle caused a decrease in the sprain occurrence. Nevertheless, the increased plantarflexion torque places the ankle in a more plantarflexed and unstable position and therefore increases the risk of an inversion sprain (Wright et al., 2000). In the current study, the combined platform successfully induced a plantarflexion angle at foot contact (-13.1°), while the contact angle was in slight dorsiflexion for the inverted surface (3.3°). Also, the peak sagittal plane angle produced by the combined surface was significant plantarflexion (-11.4°) as compared to the dorsiflexion (13.1°) produced by the inverted surface. Hence, the combined surface, placing the ankle in a more plantarflexed position increases the risk of ankle sprain occurrence.

The combined tilted surface employed in this study introduces a combined tilt of 25° inversion and 25° plantarflexion whereas the inverted surface only induces a 25° inversion. This surface condition also induced significantly higher levels of IEMG in the MG (10.79 %·s) as compared to the inverted surface (5.66 %·s). The muscle activity pattern is supported by the kinematic results with higher degree of plantarflexion (-13.1°) in the combined surface than the inverted surface (3.3°) at contact. In the frontal plane, the combined tilted platform produced smaller contact inversion angle of the ankle as compared to that of the inversion platform. Also, the peak inversion angle was significantly greater on the inverted surface landing (28.1°) as compared to the combined surface (23.0°). These results indicate that the combined surface induces slightly smaller peak inversion. This is may be explained by the orientation of the foot while landing on the surfaces. The combined surface induced the foot to be in a more diagonal position as opposed to the inverted surface, which induced a more parallel placement on the landing surface.

The significantly different kinematics of the two tilted surfaces provides evidence that the combined surface although did not produce higher inversion but induced higher levels of plantarflexion and MG muscle activity than the inverted surface. MG activity and Ankle inversion kinematics support the hypothesis of this study, but PL and TA activity was not higher for combined surface landing than inverted surface. The combined movement of inversion and plantarflexion does provoke a more unstable environment for the ankle, thus inducing greater potential threat for lateral ankle sprain. Previous studies have shown that landing on inverted surfaces did not elicit significant differences among the response amplitude in PL, TA and MG (Gruneberg et al., 2003). This study provides more insight on the type of perturbations, such as the combined tilting surface, that stimulates lateral ankle sprains.

The main limitation in this study is that the surface conditions were not randomized due to the safety concern. The inverted and combined tilted platforms presents progressively more challenges to the participants in maintaining balance after landing contact. Therefore, we did not randomize the testing conditions for safety purposes. Gruneberg, et.al. observed that pre-knowledge of landing on flat and inverted surfaces had no significant effects on the pre-activity of PL (Gruneberg et al., 2003). Therefore, the results in this study should not be significantly influenced by the condition order. Another limitation was that the landing platform used in this study proved to be a hindrance in obtaining force platform data in the two tilting surface conditions due to the noises introduced by the impact vibration of the tilting surface during landing. Future studies should focus on minimizing the impact and obtaining kinetic data to shed more light on the lateral ankle sprain.

CONCLUSION

In conclusion, the latencies of MG, PL and TA did not differ among the three surface landings. The flat surface induced higher TA activity than the two tilted surfaces. The inverted surface produced significantly higher inversion velocity and peak angle than the flat surface. However, it did not produce significantly different muscle activity as compared to the flat surface. On the other hand, the combined surface produced significantly higher MG muscle activity and ankle plantarflexion compared to the inverted surface. These findings suggest that inversion alone does not seem to pose a significant threat for lateral ankle sprains. A surface combination of plantarflexion and inversion provides a more suitable surface condition simulating lateral ankle sprains.

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APPENDICES

APPENDIX A

INFORMED CONSENT FORM

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Introduction

You are invited to participate in a research study entitled, “Effect of tilted surfaces on ankle EMG and kinematics during landing”. The purpose of this study is to examine the effects of unanticipated change in landing surface inclination (flat, inversion alone, a combination of inversion and plantarflexion) on the ankle muscle activities and ankle movements during a drop landing movement. 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 required to attend a single session of about 90 – 120 minutes in the Biomechanics/Sports Medicine Laboratory at the University of Tennessee. 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. You will then fill out a short survey about your basic information and the ankle and other lower limb injuries. Later on, your height and weight measurements will be taken. The test session will begin with a standard warm-up using a treadmill and stretching. After the warm-up, muscle electrodes will be placed on three muscles on the right leg. These electrodes are used to monitor the electrical activity of very small magnitude generated by the muscles during movement. They will not introduce any external electrical activity and cause any shock to your body. You will perform 3 Maximal Voluntary Isometric Contractions of the muscles tested. After that reflective markers will be placed on your left and right leg and foot. You will then perform landing movements from a height of 0.30 – 0.45 m onto (a) an anticipated flat surface, (b) an unanticipated flat surface, (c) an unanticipated 25° side-tilted surface and (d) an unanticipated combined surface of 25° side-tilting and 25° of forward-tilting. You will perform five landings on each surface. You will be asked to practice with the testing protocols on the platform and in the drop landing until you feel comfortable in these movements. During the testing, biomechanics instruments will be used to obtain measurements. None of the instruments will impede your ability to engage in normal and effective motions during the test. If you have any further questions, interests or concerns about any instrumentation, please feel free to contact the investigator.

Potential Risks

Risks associated with this study are minimal. Potential risks include a lateral ankle sprain and muscle strains during the dynamic movements. The landing on tilted surfaces is a common testing protocol used in studies examining ankle movements. Ample practice will be provided for both movements prior to the testing to minimize any possibility of soft tissue injuries. The investigator or a qualified research assistant in the Biomechanics/Sports Medicine Lab will be stationed close to you and provide assistance in case you lose balance. In case of any injury occurring 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 during the course of research, or for more information, please notify the principal investigator at (865) 748-1427.

Benefits of Participation

Your benefits include the opportunity to learn about the muscle activity of the ankle during sprain simulating conditions. You will also gain personal experience of the mechanisms of the ankle in controlling ankle movements in potentially injurious situations.

Compensation

You will receive no compensation for participation in this study.

Voluntary Participation and Withdrawal

Your participation is entirely voluntary and your refusal to participate at any time 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. 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 Office in the Office of Research at the University of Tennessee at (865) 974-3466.

Consent

The test has been explained fully to my satisfaction and I agree to participate. 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 do not give up any of my legal rights as a participant.

Subject's Name: ___________________________

Signature: ___________________________

Date: _________________

Investigator's Signature: ___________________________

Date: _____________________

Subject Number ___________

Participant initials ______________

APPENDIX B

Table 4. Descriptive Characteristics of Participants

Subject	**Gender (F/M)**	**Age (years)**	**Height (m)**	**Weight (kg)**
1	M	23	1.68	66.81
5	M	27	1.87	89.09
6	M	21	1.81	85.75
7	M	24	1.77	75.00
9	F	24	1.60	52.50
10	F	20	1.58	48.40
12	M	25	1.71	77.72
14	M	31	1.81	73.18
15	M	21	1.85	75.00
16	M	19	1.77	70.00
17	M	25	1.74	73.63
18	M	33	1.72	70.45
Mean		24.41	1.74	71.46
(SD)		4.25	0.09	11.68

Table 5. Subject means and standard deviations of IEMG of the ankle muscles: mean ± STD

Subject	Muscle	Flat	Inverted	Combined
1	MG (%·s)	7.36±0.79	9.68±2.14	20.66±3.61
	PL (%·s)	12.15±3.00	9.66±1.64	12.41±2.80
	TA (%·s)	8.57±7.43	6.68±2.79	12.78±1.33
5	MG (%·s)	5.64±0.63	5.17±0.99	7.08±2.28
	PL (%·s)	4.18±0.59	3.40±0.51	5.17±1.32
	TA (%·s)	22.06±4.84	16.26±3.94	4.97±6.23
6	MG (%·s)	9.18±1.06	7.27±1.19	10.38±0.93
	PL (%·s)	8.71±1.26	6.67±1.40	8.66±0.80
	TA (%·s)	23.57±3.75	17.52±5.44	8.42±2.10
7	MG (%·s)	9.83±2.02	8.11±1.92	12.37±5.09
	PL (%·s)	19.01±1.54	12.22±2.84	15.44±2.20
	TA (%·s)	27.89±0.18	10.32±2.42	15.42±3.19
9	MG (%·s)	8.48±0.89	8.10±2.44	14.13±1.60
	PL (%·s)	14.00±3.00	15.96±5.79	13.76±2.59
	TA (%·s)	22.28±5.12	23.33±9.03	12.66±4.02
10	MG (%·s)	6.45±1.01	6.05±0.80	10.81±0.81
	PL (%·s)	10.21±1.24	11.39±1.85	16.72±2.76
	TA (%·s)	15.39±3.36	16.06±3.19	15.78±2.23
12	MG (%·s)	7.31±0.77	6.02±1.71	14.77±3.58
	PL (%·s)	12.48±2.10	11.52±3.47	22.80±1.82
	TA (%·s)	19.31±2.22	13.18±2.67	23.23±3.21
14	MG (%·s)	8.38±1.67	4.29±0.37	9.22±3.11
	PL (%·s)	9.46±1.03	5.46±0.62	9.38±2.35
	TA (%·s)	27.76±3.18	13.79±2.03	8.77±1.96
16	MG (%·s)	3.28±0.55	2.51±0.57	3.69±2.40
	PL (%·s)	3.36±1.08	2.36±0.71	3.18±0.76
	TA (%·s)	15.85±8.25	6.00±0.81	3.19±0.99

Table 5. Continued.

Subject	Muscle	Flat	Inverted	Combined
17	MG (%·s)	1.08±0.34	1.03±0.24	2.67±1.55
	PL (%·s)	4.44±0.92	4.35±0.85	9.68±1.71
	TA (%·s)	19.60±5.08	13.59±4.61	9.75±1.86
18	MG (%·s)	4.93±0.95	4.03±0.70	12.95±2.47
	PL (%·s)	20.58±5.09	16.40±4.43	15.25±2.29
	TA (%·s)	22.75±7.00	22.24±7.43	15.46±1.90

Table 6. Subject means and standard deviations of ankle kinematics: mean ± STD

Subject	**Variables**	**Flat**	**Inverted**	**Combined**
1	Cont_Sagittal (deg)	-21.97±4.22	-3.31±3.99	-22.70±4.03
	Max_Sagittal (deg)	14.97±2.24	3.10±1.92	-17.04±2.00
	Cont_Inv (deg)	1.17±2.01	10.63±4.06	1.55±3.46
	Max_Front (deg)	-4.04±0.96	28.74±2.77	22.72±1.06
	Max_Inv Vel (deg/s)	99.16±42.04	716.11±113.58	619.56±88.11
	Max_Trans (deg)	-12.98±0.00	10.15±3.72	5.53±1.59
5	Cont_Sagittal (deg)	-12.03±0.88	-1.30±2.13	-11.68±1.75
	Max_Sagittal (deg)	22.97±1.39	9.16±2.29	-11.44±2.16
	Cont_Inv (deg)	10.99±0.96	17.27±1.12	11.70±2.00
	Max_Front (deg)	4.57±1.70	33.31±1.99	32.48±1.11
	Max_Inv Vel (deg/s)	-27.66±6.60	454.32±79.81	584.27±31.14
	Max_Trans (deg)	-6.92±1.21	9.55±2.22	17.93±1.63
6	Cont_Sagittal (deg)	-0.40±2.02	12.20±2.18	-9.85±3.68
	Max_Sagittal (deg)	26.53±2.03	16.34±1.93	-8.74±1.96
	Cont_Inv (deg)	2.34±1.99	19.92±1.49	9.15±1.74
	Max_Front (deg)	1.55±0.34	32.06±1.43	33.57±2.58
	Max_Inv Vel (deg/s)	59.13±12.77	654.89±64.79	643.90±69.17
	Max_Trans (deg)	-7.35±0.00	5.51±0.83	13.58±3.69

Table 6. Continued.

Subject	**Variables**	**Flat**	**Inverted**	**Combined**
7	Cont_Sagittal (deg)	-2.01±2.39	5.22±1.42	-16.76±4.12
	Max_Sagittal (deg)	23.76±1.22	9.99±2.65	-16.73±1.33
	Cont_Inv (deg)	-5.87±0.28	13.52±1.49	2.69±3.62
	Max_Front (deg)	-3.95±2.02	27.69±2.36	19.88±2.53
	Max_Inv Vel (deg/s)	81.57±33.53	738.22±43.67	542.39±197.35
	Max_Trans (deg)	-12.20±0.52	2.94±2.72	6.31±2.33
9	Cont_Sagittal (deg)	-18.26±1.20	-0.82±4.43	-9.63±5.38
	Max_Sagittal (deg)	41.65±1.07	26.08±2.85	0.87±3.15
	Cont_Inv (deg)	0.60±1.94	10.65±1.46	3.55±6.06
	Max_Front (deg)	3.09±0.31	30.65±1.21	21.76±3.03
	Max_Inv Vel (deg/s)	28.77±69.28	54.11±6.31	530.64±91.63
	Max_Trans (deg)	0.00±0.00	5.34±1.52	9.93±1.94
10	Cont_Sagittal (deg)	-22.63±1.30	-0.43±3.73	-18.01±1.36
	Max_Sagittal (deg)	31.04±2.00	18.07±3.96	-13.02±2.09
	Cont_Inv (deg)	3.12±0.41	13.38±1.41	6.74±3.23
	Max_Front (deg)	-3.00±1.78	25.43±3.42	13.61±2.62
	Max_Inv Vel (deg/s)	4.26±11.88	86.26±59.97	275.39±141.69
	Max_Trans (deg)	-4.44±0.91	5.02±1.74	4.22±2.78

Table 6. Continued.

Subject	**Variables**	**Flat**	**Inverted**	**Combined**
12	Cont_Sagittal (deg)	-8.87±0.72	-1.70±3.58	-15.09±3.31
	Max_Sagittal (deg)	28.98±2.64	12.47±1.06	-7.62±1.63
	Cont_Inv (deg)	6.33±1.37	16.21±1.46	13.30±3.21
	Max_Front (deg)	-1.97±2.90	30.12±1.92	26.85±1.91
	Max_Inv Vel (deg/s)	-13.37±29.97	455.49±73.03	490.27±62.56
	Max_Trans (deg)	-10.48±2.72	3.39±1.37	5.83±2.07
14	Cont_Sagittal (deg)	-17.39±1.37	4.37±2.64	-11.94±1.44
	Max_Sagittal (deg)	23.69±0.73	9.41±3.61	-15.49±2.15
	Cont_Inv (deg)	-3.10±1.07	12.83±1.67	0.28±1.28
	Max_Front (deg)	-4.37±0.54	22.0±1.39	17.16±1.50
	Max_Inv Vel (deg/s)	-7.28±4.15	499.74±40.32	540.85±24.17
	Max_Trans (deg)	0.00±0.00	2.06±1.39	2.62±2.34
15	Cont_Sagittal (deg)	0.86±4.71	16.16±0.91	-7.94±0.54
	Max_Sagittal (deg)	35.50±1.69	27.56±1.81	-3.88±2.26
	Cont_Inv (deg)	-4.94±1.29	13.44±2.26	1.45±3.85
	Max_Front (deg)	-10.08±1.50	22.71±1.38	18.21±2.96
	Max_Inv Vel (deg/s)	23.68±19.54	611.02±80.75	566.61±122.51
	Max_Trans (deg)	0.00±0.00	2.80±1.66	6.42±2.20

Table 6. Continued.

Subject	Variables	Flat	Inverted	Combined
16	Cont_Sagittal (deg)	-8.35±2.90	6.98±0.85	-10.37±3.59
	Max_Sagittal (deg)	30.82±2.84	14.52±1.54	-13.30±1.42
	Cont_Inv (deg)	4.96±1.46	19.78±1.74	3.64±1.81
	Max_Front (deg)	0.09±1.08	30.04±0.91	27.18±1.26
	Max_Inv Vel (deg/s)	-2.17±8.23	609.68±36.88	536.92±62.13
	Max_Trans (deg)	-5.66±1.75	12.03±1.78	9.31±1.42
17	Cont_Sagittal (deg)	-0.47±6.93	1.60±1.58	-12.99±2.49
	Max_Sagittal (deg)	24.31±0.71	7.18±2.06	-13.39±0.50
	Cont_Inv (deg)	2.51±1.20	11.59±0.66	3.75±3.90
	Max_Front (deg)	-0.87±1.52	25.50±1.05	20.28±0.85
	Max_Inv Vel (deg/s)	41.37±14.81	772.46±33.88	488.41±95.09
	Max_Trans (deg)	-8.93±0.00	7.25±0.86	3.09±1.90
18	Cont_Sagittal (deg)	0.50±3.21	1.73±1.38	-11.22±4.88
	Max_Sagittal (deg)	17.62±1.90	4.29±1.72	-17.26±0.91
	Cont_Inv (deg)	4.99±0.51	19.56±2.66	7.37±3.13
	Max_Front (deg)	-0.11±0.83	30.04±0.14	22.73±1.94
	Max_Inv Vel (deg/s)	87.37±8.18	595.31±18.38	385.19±171.22

	Max_Trans (deg)	-11.90±1.52	9.88±2.21	4.14±0.80

VITA

Divya Bhaskaran was born in Chennai, India on March 19th, 1986 to M.R. Bhaskaran and Usha Bhaskaran. She grew up in Andhra Pradesh, where she went to middle school. She graduated from Sankara Vidhyashramam Higher Secondary School in 2003, in Chennai. She went on to pursue a Bachelors degree in Sathayabama Institute of Science and Technology majoring in Biomedical engineering. She pursued her major in biomechanics and graduated in 2007. To pursue a Masters in Exercise Science, she enrolled in the University of Tennessee, Knoxville in 2007. Continuing her passion in biomechanics, she will graduate with a concentration in Biomechanics/ Sports Medicine in 2010.