Changes in Lower Limb Kinematics, Kinetics, and Muscle Activity in Subjects with Functional Instability of the Ankle Joint during a Single Leg Drop Jump

Eamonn Delahunt, Kenneth Monaghan, Brian Caulfield

School of Physiotherapy and Performance Science, University College Dublin, Health Sciences Centre, Belfield, Dublin 4, Republic of Ireland

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ABSTRACT: The purpose of this study was to identify differences in 3D kinematics, kinetics, and ankle joint muscle activity in subjects with functional instability (FI) of the ankle joint during a drop jump. Twenty-four subjects with the subjective complaint of FI of the ankle joint and 24 noninjured control subjects performed 10 single leg drop jumps onto a force-plate. Timing and magnitude of kinetic data, timing of kinematic data, and integrated EMG (IEMG) activity of the rectus femoris, peroneus longus, tibialis anterior, and soleus muscles during two 200-ms time periods either side of initial contact (IC) with the ground were analyzed and compared between groups. Subjects with FI demonstrated a significant decrease in pre-IC peroneus longus IEMG activity, which was accompanied by a change in frontal plane movement at the ankle joint during the same time period. Following IC, FI subjects were less efficient than control group subjects in reaching the closed packed position of the ankle joint. Significant differences were seen between the groups' time-averaged and peak vertical and sagittal components of ground reaction force. The altered pre-IC peroneus longus IEMG and increased inversion of the ankle joint observed in FI subjects could help to explain why subjects with FI may suffer from inversion injury to their ankle joint when subjected to an unanticipated ground contact. The kinematic and kinetic differences observed in subjects with FI may lead to repeated injury and damage to the supporting structures of the ankle joint. J Orthop Res 24:1991–2000, 2006

Keywords: ankle instability; kinetics; kinematics; EMG

INTRODUCTION

Lateral ligament complex sprains of the ankle joint commonly occur in sports with a high level of jumping and cutting activities, and especially in ball sports.[1] The presence of residual pain and functional problems (recurrent complaints of "giving way" or repeated sprain) following lateral ligament complex sprains are often reported in the literature.[2–5] These symptoms of repeated complaints of "giving way" and/or recurrent sprain have been termed functional instability (FI) of the ankle joint.[3] In sports such as basketball, the incidence of FI following lateral ankle joint inversion injury has been shown to exceed 70%.[6]

It has been suggested that a positional error of the ankle joint prior to ground contact could render the functionally unstable ankle more susceptible to recurrent inversion injury.[7] To our knowledge, to date, no study has investigated simultaneously lower limb 3D kinematics, kinetics, and ankle joint muscle activation during a jump landing technique.

Therefore, the specific aims of the study were:

1. To compare the angular displacements at the hip, knee, and ankle joints in a group of subjects with FI compared to a noninjured control group during a drop jump.
2. To compare the angular velocities at the hip, knee, and ankle joints in a group of subjects with FI compared to a noninjured control group during a drop jump.
3. To compare the kinetic patterns in a group of subjects with FI compared to a noninjured control group during a drop jump.
4. To compare the IEMG patterns of the rectus femoris, peroneus longus, tibialis anterior, and soleus muscles in a group of subjects with FI compared to a noninjured control group during a drop jump.

We hypothesized that subjects with FI would exhibit differences in time-averaged kinematics,

Correspondence to: Eamonn Delahunt (Telephone: 011-353-1-716-6506; Fax: 011-353-1-716-6501; E-mail: eamonn.delahunt@ucd.ie)

kinetics, and IEMG, when compared to a non-injured control group, which may help to explain why these subjects suffer from repeated ankle joint inversion injury.

METHODS

Subjects

Twenty-four subjects (15 male, 9 female) with the subjective compliant of FI, and 24 control subjects (16 male, 8 female) volunteered to participate in the study. Age and anthropometrical characteristics of the subjects are shown in Table 1. Inclusion criteria in the FI group were based on the criteria previously used by Caulfield and Garrett[8]: the subject reports a past history of a minimum of two inversion injuries to one ankle that required a period of protected weight-bearing and/or immobilization; the subject reports no history of fracture to the lower extremity; the involved ankle is subjectively reported to be chronically weaker, more painful, and less functional than the other at the time of testing; the subject reports a tendency for the ankle to "give way" during sporting activities; and current subjective complaints are reported to be secondary to past history of inversion sprains. None of the FI group subjects were receiving formal rehabilitation at the time of testing. Control group subjects had no history of ankle sprain or fracture of the lower extremity. None of the subjects in either group reported a history of neurological or vestibular impairments. The subjects were acquainted with the aim of the study, instructed about the experimental procedure, and asked to sign an informed consent form prior to participating in the study. The ethical committees and research review boards of the University approved the study.

EMG Data

We recorded from the rectus femoris, peroneus longus, tibialis anterior, and soleus muscles in each group. The number of muscles recorded in both groups is outlined in Table 2. EMG activity was inspected by an independent evaluator, who inspected the EMG profiles for any evidence of baseline shift, motion artifact, or mains interference. If any of the aforementioned were present, the trial was rejected, thus this accounted for the difference in the number of muscles recorded from each subject. The activity was recorded using pre-amplified electrodes (model MA-317, Motion Labs Systems, Inc., Baton Rouge, LA) applied to lightly abraded skin over the respective muscle belly. Electrode placement was carried out in accordance with the SENIAM research group recommendations.[9] The signals were amplified (gain 1,000), bandpass filtered (Blackman 61 dB) at 20 Hz (low) and 500 Hz (high), and sampled at 2,000 Hz. The signal was then full-wave rectified and averaged over a 15-ms moving window.

Table 1. Age, Height, Body Mass, and Body Mass Index of FI and Control Subjects[a]

Variable	FI Group	Control Group
n	24	24
Age (years)	25 ± 1.3*	22 ± 0.84
Height (m)	1.74 ± 0.01	1.76 ± 0.01
Body mass (kg)	72.08 ± 2.06	70.87 ± 1.9
BMI (kg m^{-2})	23.76 ± 0.49	22.72 ± 0.41

[a]Values are means ± SE.
*Significant difference from control subjects.

Table 2. Number of Subjects from Which Each Muscle Was Recorded

Variable	FI Group (n)	Control Group (n)
Rectus femoris	14	17
Peroneus longus	14	15
Tibialis anterior	13	13
Soleus	9	14

Kinematic Data

The CODA mpx 30 (Charnwood Dynamics Ltd., Leicestershire, UK), was used to provide information pertaining to 3D segment angular displacement and velocities. The infrared light emitting diode markers were attached to specific lower limb anatomical positions as outline in the Gait Analysis set-up of the CODA mpx 30 users manual. Markers were placed on the lateral aspect of the knee joint line, the lateral malleolus, the heel, and the fifth metatarsal head. Wands with anterior and posterior markers were positioned on the pelvis, sacrum, thigh, and shank. The markers were attached to the skin with double-sided adhesive tape. They were attached to the involved lower extremity in subjects with unilateral FI, while the self-reported weaker ankle was studied in subjects with bilateral FI. The left lower extremity was chosen for analysis in the control group. Marker positions were sampled at a frequency of 200 Hz.

Kinetic Data

Ground reaction forces were sampled at 500 Hz by a Bertec 4060 strain-gauge force-plate (Bertec Corporation, Columbus, OH). Sampling of EMG, kinematic, and kinetic data were synchronized.

Test Protocol

Subjects stood on a 35-cm high platform in front of a force-plate with the test leg relaxed and non-weight bearing. The subject then used the contralateral leg to propel him/herself from the platform and "stick" their landing on the test leg on the center of the force-plate. Each subject performed 10 single leg jumps onto the force-plate. No subject complained of any discomfort or pain during the testing procedure.

Data Analysis and Statistics

EMG Data

Data relating to the period 200-ms pre-initial contact (IC) to 200-ms post-IC was extracted from 10 EMG records for each muscle and each participant. Following extraction of the relevant data, EMG records were normalized with respect to peak EMG amplitude averaged from 10 records for each subject.

We chose to quantify pre- and post-IC muscle activity by means of calculating the integral EMG (IEMG) activity during two separate 200-ms linear envelopes on either side of IC. This involved calculating the area under the curve during the relevant time period. IEMG has been recommended as the most favorable method for quantifying muscle activation when utilizing surface EMG for kinesiological applications.[9] It is expressed in terms of percentage of peak activity related to the linear envelope ($\% \cdot$ ms). IEMG was calculated for each subject for both 200-ms envelopes pre- and post-IC. Group mean IEMG values for each muscle during the relevant linear envelopes were then calculated. Results are given as group mean and standard error of the mean. Differences in FI and control group IEMG activity in each muscle during the time periods 200-ms pre-IC to IC and from IC to 200-ms post-IC were tested for statistical significance using independent two-sided t-tests. Further analysis was performed for the peroneus longus and soleus muscles during the time period following IC. We chose to further analyze these muscles based upon the reported presence of short and long latency reflexes which are present in these muscles.[10] The short latency reflex for the peroneus longus has been reported to occur 41-ms post-ground contact,[10] therefore we chose to further analyze the peroneus longus IEMG during the time period from IC to 40-ms post-IC. The short latency reflex for the soleus muscle has been reported to occur between 53-ms and 45-ms post-ground contact,[10,11] therefore we chose to further analyze the soleus IEMG during the time period from IC to 40-ms post-IC. The peroneus longus and soleus muscles have also been shown to exhibit long latency reflexes, which occur approximately 90-ms post-ground contact,[11] so we also chose to further analyze these muscles during the time period from IC to 80-ms post-IC. Further analysis was not undertaken on either the rectus femoris or tibialis anterior muscles, as post-ground contact muscle activity in the rectus femoris has been shown not to be reflexive in nature,[10] while the relative contribution of reflex activity to post-ground contact tibialis anterior muscle activity has yet to be fully established.[10] The level of significance for all analyses was set at $p < 0.05$. Statistical analysis was performed by means of a commercially available software package (Excel, Microsoft Corporation).

Kinematic Data

The period from 200-ms pre-IC to 200-ms post-IC was identified for 10 trials for each subject. IC was identified using the vertical component of ground reaction force (GRF). Time-averaged profiles for hip, knee, and ankle joint 3D angular displacements and velocities were calculated for each subject. Group mean profiles were subsequently calculated. Differences in FI and control group time-averaged profiles were tested for statistical significance using independent two-sided t-tests. The level of significance was set at $p < 0.05$. Statistical analysis was performed by means of a commercially available software package (Excel, Microsoft Corporation).

Kinetic Data

Force-plate parameters relating to the time period 200-ms post-IC were extracted and converted to Microsoft Excel file format. Prior to all subsequent data analysis, all values of force were normalized with respect to each subject's body weight (BW) in Newtons. This was done with the aim of eliminating inter-group differences as a consequence of individual subjects' body mass. From this point on, all parameters of ground reaction force (GRF) were expressed as a percentage of body weight (%BW).

Magnitudes and timing of peak medial/lateral, anterior/posterior, and vertical forces as well as 3D moments and powers were identified for each jump and individual and group mean profiles were subsequently calculated. One-way ANOVA were used to test for significant differences in timing and magnitude of peak forces, moments, and powers. Furthermore, magnitudes of medial/lateral, anterior/posterior, and vertical components of GRF as well as 3D joint moments and powers were averaged over time following IC for each subject, and group mean profiles were calculated. Differences in FI and control group time-averaged profiles were tested for statistical significance using independent two-sided t-tests. The level of significance was set at $p < 0.05$ for all analyses.

RESULTS

IEMG

FI subjects showed a significant decrease in pre-IC peroneus longus IEMG ($p < 0.01$). No differences were noted between the groups' post-IC peroneus longus IEMG activity. There were no significant differences between the groups in terms of rectus femoris, tibialis anterior, or soleus IEMG either pre-IC or post-IC. Group averaged normalized IEMG activities for each muscle are outlined in Figure 1. Group mean IEMG activity in each muscle during the 200-ms periods pre- and post-IC are detailed in Table 3.

Kinematic Data

The following differences in time-averaged angular displacements and velocities at the ankle and hip joints were observed in subjects with FI. FI subjects had a more inverted position of the ankle joint during the time period from 200-ms–95-ms

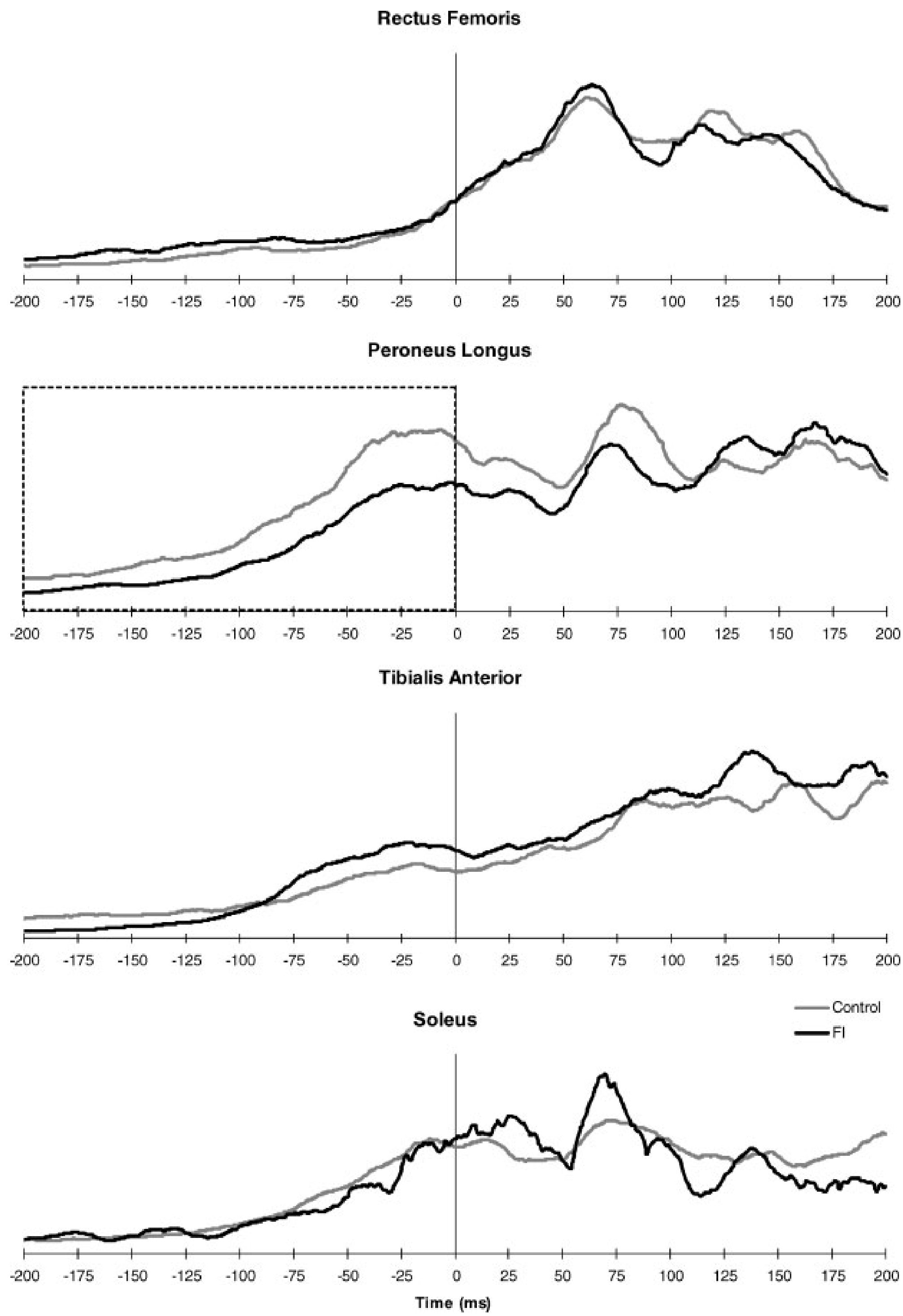

Figure 1. Group averaged normalized EMG responses 200 ms prior to and post-IC. Boxed area represents the area of statistical significance.

pre-IC ($p < 0.05$). FI subjects also had a less dorsiflexed position of the ankle joint during the time period from 90-ms–200-ms post-IC ($p < 0.05$). Subjects with FI also exhibited a change in sagittal plane ankle joint angular velocity, whereby during the time period 50-ms–125-ms post-IC they were moving towards a dorsiflexed position of the ankle joint at a slower rate than control subjects ($p < 0.05$). FI subjects also had a less externally rotated position of the hip joint during the time

Table 3. IEMG Activity during the 200 ms Periods Pre- and Post-IC[a]

Variable	200-ms Pre-IC–IC		IC–200-ms Post-IC		IC–40-ms Post-IC		IC–80-ms Post-IC	
	FI Group	Control Group	FI Group	Control Group	FI Group	Control Group	FI Group	Control Group
Rectus femoris	46.77 ± 7.36	37.11 ± 3.69	159.61 ± 4.64	163.92 ± 8.32				
Peroneus longus	54.03 ± 2.67*	81.33 ± 8.69	127.77 ± 9.62	137.03 ± 7.11	21.08 ± 2.17	26.99 ± 2.83	44.96 ± 4.89	55.26 ± 4.79
Tibialis anterior	188.32 ± 25.65	177.23 ± 20.7	601.97 ± 73.08	522.54 ± 69.64				
Soleus	56.49 ± 5.91	63.09 ± 7.47	138.05 ± 6.70	148.83 ± 7.82	27.48 ± 3.5	29.63 ± 3.23	58.97 ± 4.89	61.77 ± 4.87

[a]Values are means ± SE expressed in $\% \cdot$ ms.
*Significant difference from control subjects.

period from 200-ms–55-ms pre-IC ($p < 0.05$). These kinematic changes are shown in Figure 2. No other significant differences were noted between the groups in terms of lower limb kinematics.

Kinetics

The following time-averaged kinetic differences were observed in subjects with FI. FI subjects had an increase in the vertical component of GRF during the time period 35-ms–60-ms post-IC ($p < 0.05$) as well reaching their peak vertical GRF earlier than control subjects (60-ms post-IC vs. 75-ms post-IC) ($p < 0.01$). FI subjects had a more medially directed GRF during the time period 85-ms–105-ms post-IC ($p < 0.05$). FI subjects had an increased posterior GRF during the time period 75-ms–90-ms post-IC ($p < 0.05$) as well as reaching their peak posterior GRF earlier than control subjects (85-ms post-IC vs. 115-ms post-IC) ($p < 0.01$). FI subjects had less eccentric sagittal plane power generation during the time period 60-ms–145-ms post-IC ($p < 0.05$). No other significant changes were noted between the groups in terms of kinetics. Table 4 outlines the timing of the components of the GRF. Figure 3 shows the time-averaged components of the GRF during the period 200-ms post-IC.

DISCUSSION

The finding of reduced activation in the peroneus longus muscle in the period immediately prior to IC agrees with the findings of Caulfield et al.[12] However unlike the study of the Caulfield et al.,[12] we were able to simultaneously record the 3D position of the ankle joint. The observed reduction in peroneus longus activity was accompanied by a statistically significant inverted position of the ankle joint during the time period from 200-ms–95-ms pre-IC. Although subjects with FI did not differ from control subjects in terms of frontal plane movement at the ankle joint upon IC, we believe that the finding of a more inverted position of the ankle joint from the time period 200-ms–95-ms pre-IC as well as a decrease in peroneus longus IEMG activity during the same time period is significant.

The main function of the peroneal muscles is to control the amount of inversion occurring at the ankle joint.[13] The ability of the peroneal muscles to reflexively protect the ankle joint when subjected to a sudden inversion perturbation has been questioned.[10,14,15] Consequently, it has been suggested

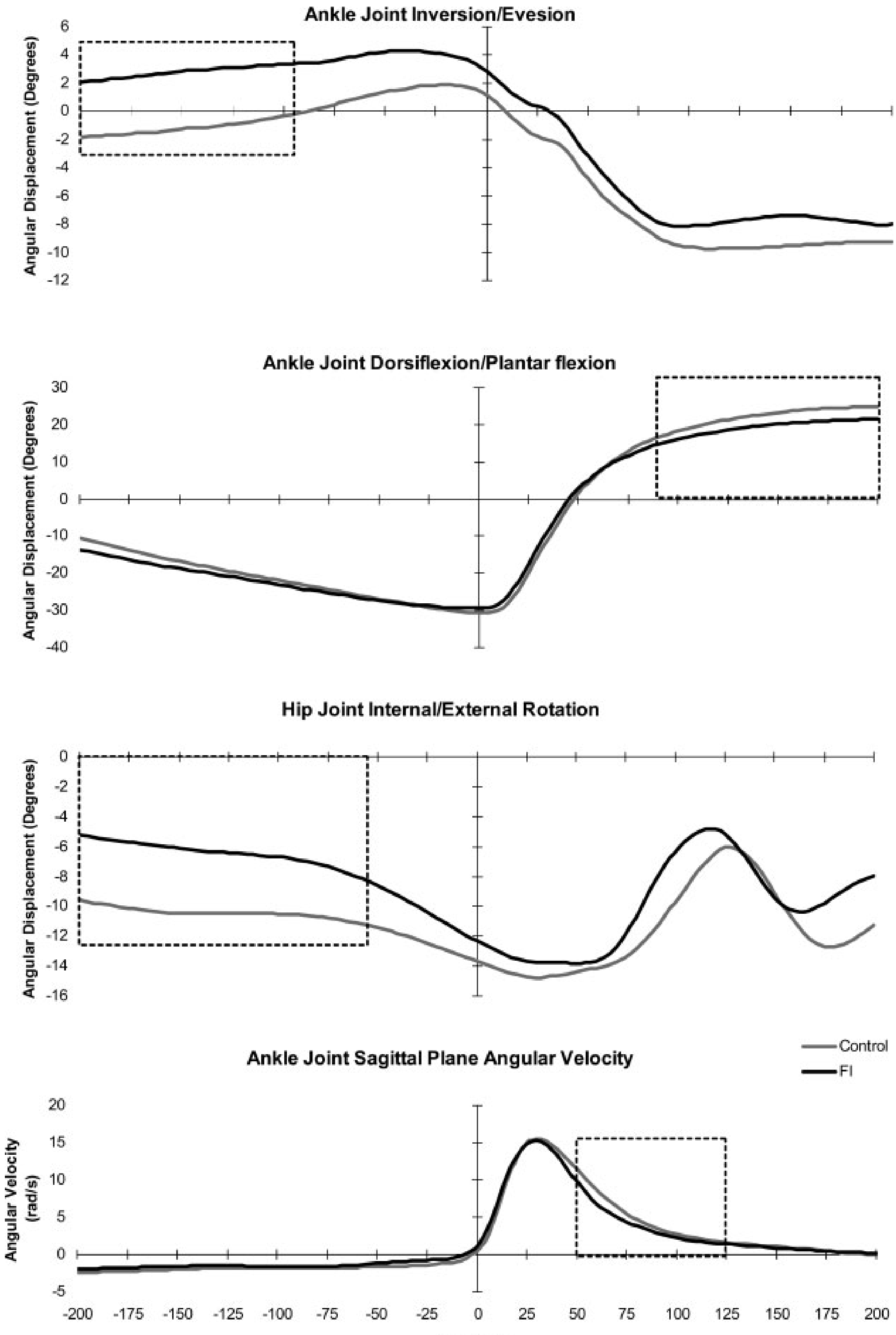

Figure 2. Kinematic differences at the hip and ankle joints. Boxed area represents the area of statistical analysis. In the hip internal/external rotation curve, external rotation (negative). In the ankle inversion/eversion curve, inversion (positive). In the ankle dorsiflexion/plantar flexion curve, dorsiflexion (positive). In the ankle sagittal plane angular velocity curve, dorsiflexion (positive).

Table 4. Timing of Peak GRFs Post-IC[a]

	Timing of Peak Forces Post-IC (ms)		Level of Significance	
Direction of Force	FI Group ($n = 24$)	Control Group ($n = 24$)	F-Value	p-Value
Vertical	60 ± 2.61*	75 ± 3.178	7.77	0.0076
Lateral	65 ± 3.03	65 ± 5.35	0.23	0.64
Medial	130 ± 10.59	150 ± 13.91	0.25	0.62
Posterior	85 ± 5.14*	115 ± 3.03	11.42	0.001

[a]Values are means ± SE expressed in ms.
*Significant difference from control subjects.

that if the peroneal muscles are to protect the ankle joint against a sudden unexpected inversion perturbation, then pre-IC muscle activity in the peroneal muscles is necessary to provide adequate joint stabilization and prevent an inversion injury.[15] However, the dilemma lies in the fact that not all ankle joint sprains occur at the time of expected contact with the ground. Garrick [16] has

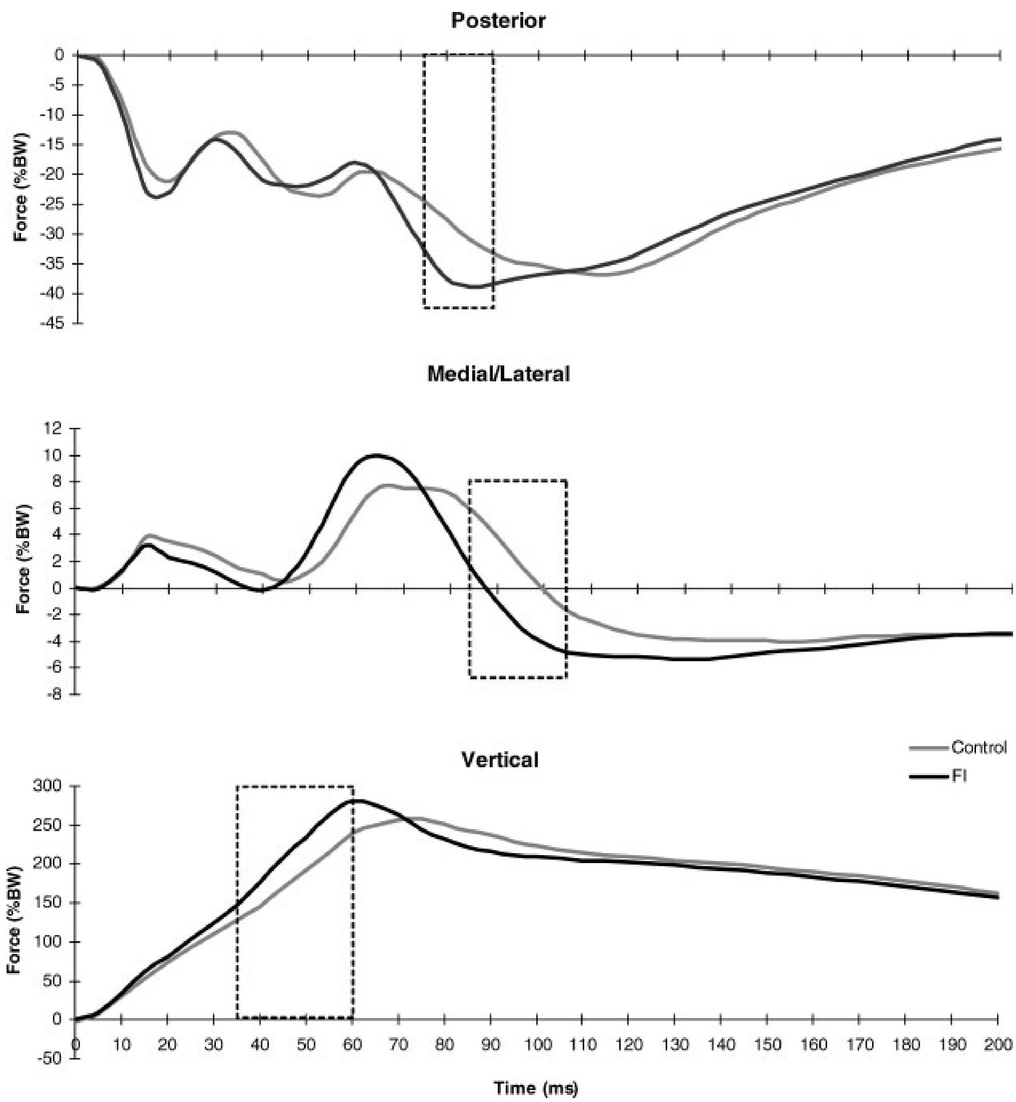

Figure 3. GRF during 200-ms post-IC. Control and FI group time-averaged mean. In the medial/lateral force curve, medial (negative). Boxed area represents the area of statistical significance.

proposed that one of the mechanisms of inversion injury of the ankle joint involves landing on an irregular playing surface (e.g., a rutted playing field or another player's foot). The results of our study provide a plausible hypothesis as to why subjects with FI may injure their ankle joint following an unexpected ground contact incident. It is evident from our results that the decrease in peroneal longus activity prior to the expected IC with the ground leaves the ankle joint in a vulnerable position (i.e., more inverted position) and any unanticipated ground contact could cause a hyperinversion injury. Our study, however, suffers from the limitation that we did not record the activity in the peroneus brevis muscle. We cannot extrapolate our findings of a decrease in peroneus longus IEMG to a similar change in peroneus brevis function, and thus feel that future studies should try to evaluate muscle activity in both peroneals.

Subjects with FI were observed to have a less dorsiflexed position of the ankle joint during the time period 90-ms–200-ms post-IC. During the same time period, FI subjects also had a decreased sagittal plane angular velocity whereby they were dorsiflexing at a decreased rate compared to control subjects, as well as a decreased sagittal plane eccentric power generation during the same time period. These results suggest that FI subjects are not as efficient as control group subjects in reaching the closed packed dorsiflexed position of the ankle joint. It has been suggested that limited dorsiflexion range of movement may predispose to the development of lateral ankle joint sprains in children.[17] The authors of that study concluded that tightness of the triceps surae muscle complex could predispose to ankle joint injury if the ground reaction forces following impact are not absorbed by controlled dorsiflexion, and thus suggested that children with tight triceps surae muscle complexes should undergo a regimen of stretching exercises to address this issue. The results of that study are supported by the findings of the present study which has shown that subjects with FI have a decreased rate of dorsiflexion following ground impact during a jump landing task. We believe that tight calf musculature may be a factor contributing to this finding and would suggest that stretching of the calf musculature should be incorporated into rehabilitation programs following inversion injury. Another explanation for the findings noted above could be a restriction in posterior talar glide. Denegar et al.[18] have shown that in subjects with a history of ankle joint inversion injury, physiological range of motion may be restored in the absence of normal accessory joint motion, as evidenced by full passive range of motion of dorsiflexion but decreased posterior talar glide. Further evidence of changes in accessory joint motion, and in particular posterior talar glide, can been seen from the results of a study by Green et al.[19] These authors reported a more rapid restoration of dorsiflexion range of motion and subsequent normalization of gait parameters in subjects treated with posterior talar mobilizations following inversion injury. Therefore, we suggest that in addition to stretching of the calf musculature, accessory joint motion should also be assessed following inversion injury. Furthermore, we believe that the decreased dorsiflexed position of the ankle joint and the concomitant decreased rate of dorsiflexion observed in the subjects with FI may contribute to the changes noted in the posterior component of GRF. During dorsiflexion, the talus undergoes posterior sagittal translation and posterior sagittal rotation. If there is a delay in ankle joint dorsiflexion, this may result in an increased posterior GRF, due to the position of the body mass and center of gravity in relation to the base of support, which in this case would be a less dorsiflexed position of the ankle joint. Consequently, this may lead to increased stress being transmitted to the ankle joint articular surfaces.

FI subjects have been shown in this study to exhibit a significantly increased time-averaged vertical component of GRF and a quicker onset of the vertical component of GRF compared to the control group. This finding agrees with the findings of Caulfield and Garrett[8] who indicated that FI subjects exhibited an increased vertical component of GRF during the time period from 24-ms–36-ms post-IC. These differences noted may have important clinical implications. FI subjects reached their peak vertical GRF at 60-ms post-IC compared to 75-ms post-IC in the control group. FI subjects only begin to dorsiflex at approximately 50-ms post-IC (Fig. 2). Therefore, at 60-ms post-IC, the ankle joint is still in a vulnerable position having yet not reached the closed packed position. Consequently, increased loading of the ankle joint during this period of time may lead to undue stress being transmitted to the articular surfaces and supporting ligaments, resulting in repeated injury and consequent damage to ankle joint structures.

During the time period 85-ms–105-ms post-IC, FI subjects exhibited a more medial GRF compared to the control group. These results disagree with those observed by Caulfield and Garrett[8] who found a more lateral GRF in FI subjects during the time period from 30-ms–40-ms post-IC.

Differences observed may be the result of differences in the subjects recruited for both studies. Although the same classification was used to recruit subjects with FI, no measures were taken to control for differences in the number of ankle sprains experienced, the number of “giving way” episodes experienced, or the level of activity during which ankle sprains are experienced. To date, there is no universally accepted definition to quantify the subjective complaint of FI of the ankle joint. We feel that it is now necessary that a consensus statement be established to quantify FI. This consensus statement should include data such as how many episodes and during which activities do feelings of “giving way” occur. Furthermore, every effort should be made in the future to match subjects based on age, sex, height, weight, and level of sporting activity. The increased medial component of GRF force observed in the present study may provide some indication as to why subjects with chronic lateral ankle joint instability have been found to have an increased incidence of degenerative changes of the articular cartilage over the medial half of the talar and tibial surfaces of the ankle joint.[20] D’Ambrosia and Shoji[21] have shown that disruption of the lateral ankle joint ligaments places a greater than normal load on the medial weight-bearing surfaces of the joint. Therefore, in the presence of lateral ankle instability, loading of the medial weight-bearing surfaces of the joint could be augmented by an increase in medially directed force across the joint.

The significance of the altered hip rotation observed in the FI group prior to IC cannot be fully elucidated. We can only conjecture that this observed difference provides further evidence that the neuromuscular impairments observed in subjects with FI are not confined to the ankle joint, but rather manifest further up the kinematic chain, agreeing with the conclusion of Hertel[22] that there are central neural adaptations to peripheral joint conditions.

A limitation of our study was that we did not take any measures to control for foot posture. The changes in IEMG, ankle joint kinematics, and subsequent GRF could have been caused by differences in foot posture between the groups. One particular concern would be the presence or absence of a cavus or cavo-varus foot type in the FI group. It has been shown that feet with cavus or cavo-varus deformity are more frequent in subjects with chronic lateral ankle joint instability.[23] Some authors have suggested that such foot postural alignments can alter ankle joint mortise contact sites and lateral ligament complex strain.[24,25] Furthermore, Brandes et al.[26] have suggested that the cavo-varus foot position places the peroneus longus at a mechanical disadvantage, reducing its moment arm and increasing frictional forces at the lateral calcaneal process and the cuboid notch which may subsequently lead to attritional failure. Therefore, we feel that future studies investigating subjects with FI should include a foot postural analysis.

CONCLUSION

We have shown that subjects with FI exhibit deficits in arthrokinematics and neuromuscular control which are not without consequence in terms of potential repeated injury to the functionally unstable ankle joint.

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