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14. ABSTRACT: The overall aim of this research is to gain insight into the etiology of tibial stress fractures. Three dimensional motion analysis data along with structural data will be collected from 400 subjects (200 at each site) over a 3-year period. 30 of the subjects will have sustained a tibial stress fracture prior to the study and the other 370 will have not. Subjects will be recruited primarily from track teams, running clubs, and physicians local to the University of Delaware and University of Massachusetts. Within this Annual Report, information concerning adherence to work objectives, preliminary results with respect to the proposed hypotheses, and reportable outcomes are presented for the third year of the investigation. Overall, we have adhered to most work objectives and have proposed plans for rectifying any discrepancies. The preliminary analysis of the data demonstrates encouraging results and support of most hypotheses.					
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INTRODUCTION

Stress fractures can be extremely costly to the military in terms of both time and medical expenses. The tibia is a common site for such injuries and has been most often associated with running, an activity common to all military training. Stress fractures are among the top 5 cited lower extremity injuries sustained by runners (Clement et al., 1981; Kowal, 1980; James et al., 1978; Jones, 1983; Pagliano and Jackson, 1980; Reinker and Ozburne, 1979). They are among the most serious of running-related overuse injuries as they take long to heal and if untreated, can progress to a macrofracture. Females are a growing military contingency and appear to be particularly susceptible, as it has been noted that they are twice as likely to experience a stress fracture as their male counterparts (Brudvig et al, 1983; Pester and Smith, 1992; Reinker and Ozburne, 1979).

Structural and biomechanical factors have been suggested in the cause of stress fractures. However, these mechanisms are not well understood. Therefore, the purposes of this study are 1) to compare the structure and mechanics of runners who have sustained a tibial stress fracture to those who have not, 2) to gain an understanding of which combination of factors (structural and/or biomechanical) are predictive of tibial stress fractures, and 3) to assess whether mechanics are altered following a tibial stress fracture. Once the factors associated with stress fractures are identified, future work will focus on formation and testing of a simple screening tool to facilitate identification of those at risk.

This is a dual-site investigation (University of Delaware & University of Massachusetts, Amherst) which began on September 1, 2000 and has been under investigation for six years. This Annual Report will focus on results after the sixth year of the study. We have been granted a no-cost one year extension, making this the penultimate year of the study.

BODY

Summary of Methodology

The overall aim of this research is to gain insight into the etiology of tibial stress fractures. Three dimensional motion analysis data along with structural data will be collected from 400 subjects (200 at each site) over a 3-year period. A minimum of 30 subjects will have sustained a tibial stress fracture prior to the study. Subjects will be recruited primarily from track teams, running clubs, and physicians local to the University of Delaware and University of Massachusetts. All subjects will be females between the ages of 18 and 45 and will be free of lower extremity injury at the time of testing. Lower extremity kinematics and kinetics will be collected during running. In addition, radiographs of both tibiae will be taken as well as clinical measures of lower extremity alignment. Subjects will then report their exposure data (mileage, intensity, terrain) as well as any injuries they have sustained each month via a custom developed webpage which will serve as a database for this information. If a subject reports a tibial stress fracture/reaction, the site coordinator will be notified automatically and the subject will be asked to return for a second running analysis once the fracture has healed and they are cleared to run by their physician. The structural and biomechanical factors leading up to a tibial stress fracture will be assessed. In addition, comparisons will be made of mechanics before and after the stress fracture to determine whether subjects revert to their pre-injury mechanics. If relationships between mechanics and injury are established, future interventions including gait retraining should be explored.

Statement of Work

We were granted a one year extension in order to continue our recruitment of subjects to increase our number of stress fractures. The beginning of this extension (Sept 2005) was coincident with the start of a new post-doctoral fellow we had hired, who would continue the coordination of the project. Unfortunately, after accepting the position, the individual had to decline at the last minute due to personal reasons. We began a new search, conducted interviews and hired a postdoctoral fellow to take this position. However, the individual was completing his PhD and would not be able to begin until March. Once we were aware of this, we contacted the DOD and requested another extension which we were granted. Thus, our progress over the past year has been limited. However, despite this, we have been able to collect 16 additional subjects, presented six abstracts at national meetings, presented seven invited talks and published three papers, all related to this research. Due to the number of stress fractures that the University of Delaware male track team has been sustaining, we have begun to collect data on these athletes this year as well. We hope that this will help to increase the number of prospective tibial stress fractures we will capture. Our preliminary data suggests that individuals with tibial stress reactions (early stages of bony injury that we have operationally defined) exhibit similar mechanics to those who have documented stress fractures. If this continues to be the case, we may combine these prospective injuries in order to increase our statistical power.

Based upon our retrospective and prospective findings, we have begun a preliminary study aimed at reducing lower extremity loading during running. This involves providing the runners with realtime feedback on their tibial shock during running. Preliminary results are promising suggesting that the retraining can result in a 30-50% reduction of loading parameters during running. In addition, they have been able to sustain these changes at a one-month follow-up. These data are being presented at the American Society of Biomechanics (ASB) Meeting in September. The abstract is included in Appendix B.

Along with the stress fracture injuries, we are also examining the mechanics related to other injuries including iliotibial band syndrome and patellofemoral pain syndrome. Manuscripts on these topics are in process. The prospective data from subjects who sustain iliotibial band syndrome is also being presented at the ASB meeting. This abstract was nominated for an award which will be decided upon at the upcoming meeting. This abstract is also included in the Appendix B.

Between the two data collection sites, the following objectives were outlined in the approved Statement of Work for the fifth year. We have continued to address these objectives during the one year extension at the University of Delaware site. These objectives included:

1. Recruitment of additional subjects to assist in capturing more tibial stress fractures (Added following low number of tibial stress fractures recorded by end of year 5)
2. Complete data collection and reduction on any subjects who have sustained a fracture
3. Complete follow-ups
4. Re-collect data on control group of subjects, who did not sustain a fracture
5. Complete predictive model based on all subjects who sustained a tibial stress fracture during the course of the study
6. Complete analysis of post-fracture data to determine whether the injury resulted in a change in mechanics

7. Three manuscripts accepted: one regarding predictive model of tibial stress fractures, a second regarding influence of tibial stress fracture on mechanics, and the third concerning the implication of gait retraining to reduce injury risk.

Adherence to Work Objectives

1) Recruitment of Subjects

To date, data have been collected on a total of 430 subjects: 232 at the University of Delaware and 198 at the University of Massachusetts. Although the initial target of 400 runners enrolled into the study has been met, we will continue to recruit runners into the study for an additional year to increase the likelihood of more prospective stress fractures occurring during the study. In addition, this will allow us to continue to follow up with those added in the 5th and 6th year of the study.

As with all prospective studies, the exact number of injuries that will occur in the study sample is unknown. The reported incidence of stress fractures ranges from 1-25% (Bensel et al., 1983; Brudvig et al., 1983; Kowal, 1980; McBryde et al., 1981; Milgrom et al., 1989, Reinker et al., 1979; Zernicke et al., 1993). Women are reported to be at significantly greater risk, with one study reporting a twofold increase of bilateral stress fractures over men (Pester & Smith, 1992). We based our power calculations on a 5% incidence rate. Therefore, given 400 subjects, we expected 20 fractures. To date, we only have 6 prospective tibial stress fractures. We are hopeful that continuing to recruit runners in the higher risk, 18 to 30 years age group during the one year no-cost extension will facilitate capture of more tibial stress fractures.

2) Collection of Data on those who have sustained a stress fracture

The data from the tibial stress fracture group prospectively are included in the Reportable Outcomes section in a comparison with a matched control group of subjects who have not sustained a fracture. Due to the low number of tibial stress fractures or reactions that have occurred during the study so far, we have also included a comparison of all subjects who have sustained a lower extremity stress fracture (pelvis and distally) to a matched control group

To date, eight tibial stress fractures in six individuals have been recorded prospectively. Based on a study by Frederickson et al (1995), we have considered a tibial stress reaction to be the early stages of a stress fracture. In the grant, we operationally defined a tibial stress reaction as pain located along a diffuse area of the tibia (and not in the muscle compartments) that worsens with running and is relieved with rest. Some runners will discontinue or reduce their running in response to diffuse tibial pain. However, we proposed exploring their mechanics, as well, as we believed that these data will help lend insight into the etiology of tibial stress fractures. To date, we have recorded 13 tibial stress reactions in 8 individuals. Following comments made by the reviewer of the fourth year report, we have not pooled these data with with tibial stress fractures. Results from these analyses are presented separately in the Reportable Outcomes section.

3) Follow-ups

Subjects have been tracking their monthly running exposure and injuries since their initial visit and these data have been input into the database. The database continues to function properly and subjects have

been logging in on a monthly basis to record their mileage and injuries. A summary of the injuries reported has been summarized in the Reportable Outcomes section.

364 subjects have now completed their participation in the study, including their two year follow up. 189 subjects from the University of Delaware have completed, and 175 at the University of Massachusetts.

The compliance rate for subjects who continue to report mileage and injuries for the follow up part of the study is high, and stands currently at 87%, a slight decrease on the 91% compliance rate reported last year. This is still a positive result, since more subjects have now been enrolled in the study for a longer time, providing greater opportunity for attrition. Dropouts are defined as a subject not having entered a monthly report into the website for 12 or more consecutive months. Subjects who have not responded to the monthly email request for their running data for a shorter period are contacted by telephone to obtain backdated monthly information. This method seems to have been successful. To date, a total of 96 subjects have dropped out of the study. In addition, 17 subjects that have stopped running for various reasons have withdrawn from the study. This has resulted in an overall attrition rate of 26%. This is acceptable for a follow up study of this long duration with such a large number of subjects enrolled, and is not a cause for concern.

Currently, compliance rate is calculated as the number of monthly responses submitted by a subject being divided by the number of monthly requests for data. Additional entries that were received from some of the early recruits to the project, backdating their records to the months before the website was online, are not included. Furthermore, any erroneous double submissions of the same data were excluded from the total number of submitted entries for an individual. We believe these measures have resulted in an accurate indication of compliance rate during follow-up.

Previously, the reviewers of the Annual Report have suggested that the self-report injury information collection forms on the website may contain items that are hard for the participants to judge due to anatomical and medical terms being used. If self diagnosed initially, subjects are encouraged to report their injuries after they have been diagnosed by a medical professional. To date, only 152 of 981 (15%) of prospective injuries reported to date were diagnosed by someone other than a medical professional. This is similar to last year when 127 of 919 (14%) prospective injuries reported to date were diagnosed or treated by someone other than a medical professional and represents a consistent improvement on the third year when 53 of 226 (23%) injuries were self-reported. We believe this maintained improvement is due to following up self-reported injuries by email to determine whether a medical professional was consulted at any time for the injury.

Subjects are encouraged to contact us if there is a question regarding their injury. They are also provided a space for comment on the online form regarding their injury. When any injuries related to the anterior lower leg are reported a clinician on the project has followed up with a telephone call. Therefore, we are able to further confirm the diagnosis. Any reported tibial stress fractures must be confirmed by x-rays, bone scans or MRIs. Tibial stress reactions have been operationally defined as bony pain specifically along the distribution of the tibia that is worsened with impact loading and relieved with rest. There is indication in the literature (Fredericson et al., 1995) that these stress reactions are the early stage of a stress fracture. Any subjects with reported tibial stress reactions have been contacted by a member of our research team to further confirm the diagnosis.

4) Control group of uninjured subjects

Data from seven subjects who did not sustain any injury during at least 12 months of follow-up has been collected. These runners will serve as the control when assessing changes in mechanics following a

stress fracture. We intend to continue to collect data from uninjured subjects for the control group during the no-cost extension. These data will be included in the final report.

5) Predictive model based on the data of subjects who have fractured during the course of the study to date

Due to the lower than expected occurrence of tibial stress fractures in subjects enrolled in the study, we have focused our predictive model on the retrospective tibial stress fracture data. We hypothesized that the magnitude of tibial shock would discriminate between runners with and without a history of tibial stress fracture, since preliminary results indicated that this variable was consistently higher in runners with tibial stress fracture. A binary logistic regression was carried out to determine whether PPA predicted group membership.

The results of the binary logistic regression suggested that increased tibial shock is related to an increased likelihood of being in the RTSF group. The model indicated that for every 1g increase in PPA, the likelihood of having a history of TSF increased by a factor of 1.361 (95% confidence interval 1.020 to 1.816, $p = 0.036$). According to the model chi-square statistic, the model is significant ($p = 0.020$). It also predicted group membership correctly in 70% of cases. The Nagelkerke R square value is 0.169, suggesting that 17% of the variance between the two groups was explained by PPA. These results are detailed in a manuscript that has been published recently by Milner et al. (2006) (see appendix E).

6) Analysis of pre-post fracture mechanics

To date, six runners with 8 tibial stress fractures have been recorded prospectively. All of these have now returned to the laboratory for a post-injury gait reassessment. These data are presented in the Reportable Outcomes section. In addition, the data from the tibial stress fracture group prospectively are also included in the Reportable Outcomes section in a comparison with a matched control group of subjects who have not sustained a fracture. Due to the low number of tibial stress fractures that have occurred during the study so far, we have also included a comparison of all subjects (30 fractures in 22 individuals) who have sustained a lower extremity stress fracture (pelvis and distally) pre and post-injury and to a matched control group.

7) Abstract and manuscript submission

Manuscript Submission

Two articles have been published in peer-reviewed journals. The article, “Biomechanical factors associated with tibial stress fracture in female runners”, was published in *Medicine and Science in Sport and Exercise*. A second article, “Free moment as a predictor of stress fracture in distance runners”, has been accepted for publication in the *Journal of Biomechanics*. In addition, a third article, “Gait retraining in runners”, was published in *Orthopedic Physical Therapy Practice* (Appendix E).

Two further articles are currently in review. The first, “Retrospective biomechanical investigation of iliotibial band syndrome in competitive female runners,” is in review with *Clinical Biomechanics*. The second article titled, “Does loading during early stance contribute to tibial stress fractures?” is in review with the *Journal of Bone and Joint Surgery*.

A number of other manuscripts are planned for the next year including one on prospective stress fractures/reactions as well as two other injuries of high prevalence, iliotibial band syndrome and patellofemoral pain syndrome.

Abstract Submission

In the past year, six additional abstracts have been submitted and were accepted for presentation. Three abstracts were presented at the American College of Sports Medicine National Meeting in Nashville, Tennessee and three were presented at the International Society of Biomechanics/ American Society of Biomechanics Combined Meeting in Cleveland, Ohio in August 2005. The references are provided in the Reportable Outcomes section and the complete abstracts are included in Appendix B. In addition, one abstract was presented at the Center for Biomedical Engineering Research Symposium held at the University of Delaware.

KEY RESEARCH ACCOMPLISHMENTS

- Two articles have been accepted in peer-reviewed journals about the relationships between history of tibial stress fracture and differences in kinematic, kinetic and structural variables and the mechanics associated with iliotibial band syndrome.
- To date, 13 abstracts that have been presented at various national and international conferences about the incidence of lower extremity stress fractures and their relationship to kinematic, kinetic and structural variables, the main thrust of the study.
- Additionally, a further nine abstracts concerning the relationships between lower extremity mechanics and three common running injuries: iliotibial band friction syndrome, plantar fasciitis and patellofemoral pain syndrome have been presented.
- The main focus of this study is the elucidation of the relationships between lower extremity structure, mechanics and the occurrence of tibial stress fractures. However, the large database of biomechanical, training and injury data that is being compiled during the study is proving to be a valuable source of retrospective and prospective information relating to other running injuries.
- At completion, the database generated from the 400-plus runners enrolled into this study will be a very comprehensive record of the biomechanics of female runners, their injury history and prospective injuries over a two year period. This will prove to be an invaluable resource not only in relation to stress fractures, but the many other running injuries that are common and result in time lost from training for both civilians and military recruits.

REPORTABLE OUTCOMES

This section contains all of the Reportable Outcomes to date:

- 1) Retrospective tibial stress fracture data (n=24) used as basis for the manuscript that was submitted
- 2) A summary of the prospective tibial stress fracture data (eight fractures in six individuals)
- 3) A summary of all the lower extremity prospective stress fracture data
- 4) A summary of the pre and post injury data from the eight prospective tibial stress fractures in six individuals that have returned for a second assessment following recovery from injury
- 5) A summary of the pre and post injury data from the 30 prospective lower extremity stress fractures in 22 individuals that have returned for a second assessment following recovery from injury
- 6) A summary of the prospective tibial stress syndrome data (eight reactions in 13 individuals)
- 7) Details of the abstracts presented based on data collected during this study
- 8) Other presentations made
- 9) A summary of the information recorded in the database.
- 10) A summary of degrees obtained that are supported by this award
- 11) A summary of employment and research opportunities applied for and received based on experience and training supported by this award

Note: Since there have been no additional stress fractures over the past year due to the lapse in personnel, the data remains essentially unchanged from the previous report.

1) Summary of data on female runners who had sustained a tibial stress fracture previously

Aim 1: Determine whether differences in structure and mechanics exist between subjects with a prior tibial stress fracture to those who have not sustained a fracture.

At present, we have data for retrospective tibial stress fractures have been reported in 24 subjects. This group (RTSF) was matched with 24 control subjects (CON), who have never sustained any stress fractures, to enable assessment of the lower extremity structural and biomechanical differences between the two groups. The groups were matched for monthly running mileage and age, to remove the influence of these potentially confounding factors (Table 1).

Table 1: Mean (\pm standard deviation) monthly running mileage and age of the TSF and CON groups

	Mileage (miles/ month)	Age (years)
TSF (n=24)	121 \pm 46	29 \pm 11
CON (n=24)	119 \pm 47	26 \pm 9

Ground reaction force (GRF), kinematic data, and tibial acceleration data were recorded and averaged from 5 running trials. Radiographs of the distal lower extremity were used to calculate the tibial area moment of inertia (Milgrom et al., 1989). Each subject underwent a structural evaluation by an experienced physical therapist.

Hypothesis 1.1: Runners who had sustained a previous TSF would exhibit differences in kinetic variables including increased instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to controls.

Subjects who had sustained a tibial stress fracture previously exhibited significantly greater instantaneous and average vertical loading rates (Figs. 1 and 2). No differences in impact peak, peak vertical and braking forces or leg stiffness were observed between the two groups (Table 2). This lack of difference in ground reaction force peaks between RTSF and CON groups has been reported previously (Crossley et al., 1999; Bennell et al., 2004). However, an increase in the average loading rate during braking was found in the RTSF group (Fig. 3). These existing studies did not consider loading rates in their comparisons; loading rates have consistently shown differences between RTSF and CON groups in our comparisons.

Average and instantaneous loading rates during braking have not been reported on in previous years. However, this secondary component of the ground reaction force peaks at approximately 50% of body weight and represents a substantial load to the lower extremity during the stance phase of running. It may be that differences here, multiplied over the 1000's of steps made by the distance runner, make a significant contribution to injury risk. As loading rates in the vertical direction have been increased in subjects with stress fractures, we decided to investigate loading rates during braking, in addition to peak braking force in the anteroposterior direction.

Additionally, individual joint stiffness, the change in joint angle over change in joint moment, was also investigated for the first time this year. Thus far, the global measure of leg stiffness during the first half of stance has not appeared to be related to the incidence of tibial stress fracture. Therefore, we chose to investigate the individual knee and ankle stiffness in the sagittal plane. We evaluated this stiffness over the period from foot strike to peak knee flexion, i.e. during loading of the lower extremity. Subjects with a history of tibial stress fracture had significantly higher knee joint stiffness than the control group (Fig. 4), but no difference was observed at the ankle. A stiffer knee may result in less shock attenuation by the lower extremity, thereby increasing the risk of stress related injuries.

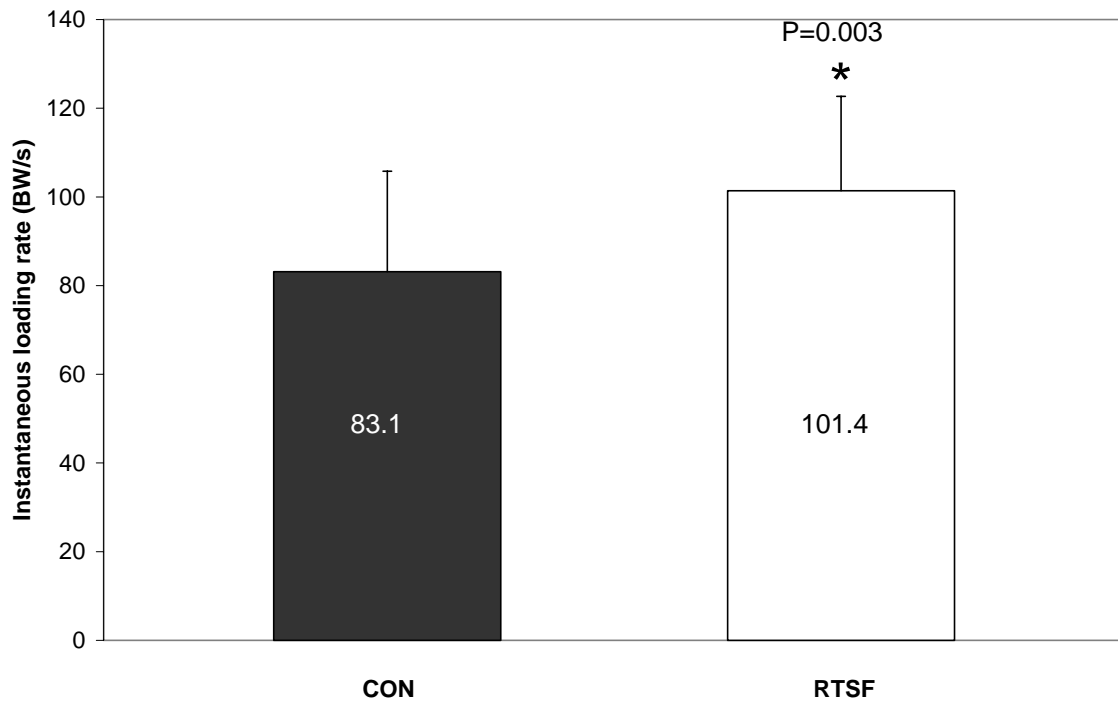


Figure 1: Instantaneous loading rate in subjects who had a previous tibial stress fracture versus healthy controls (* = significantly greater than controls).

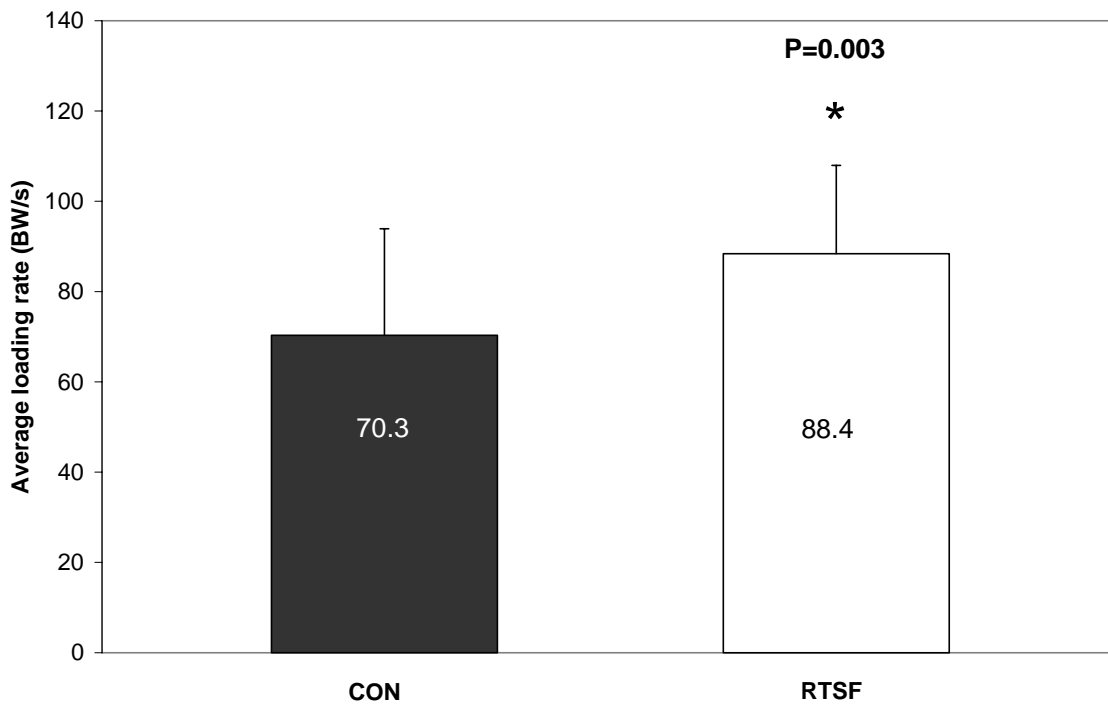


Figure 2: Average vertical loading rate in subjects who had a previous tibial stress fracture versus healthy controls (* = significantly greater than controls).

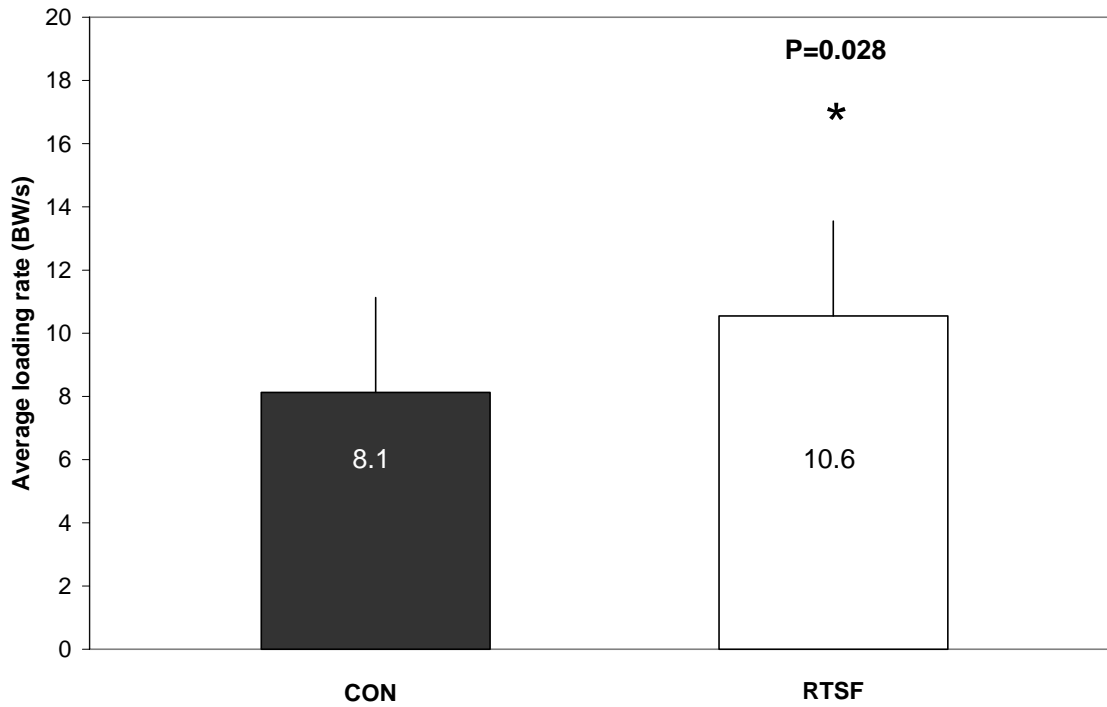


Figure 3: Average anteroposterior loading rate in subjects who had a previous tibial stress fracture versus healthy controls (* = significantly greater than controls).

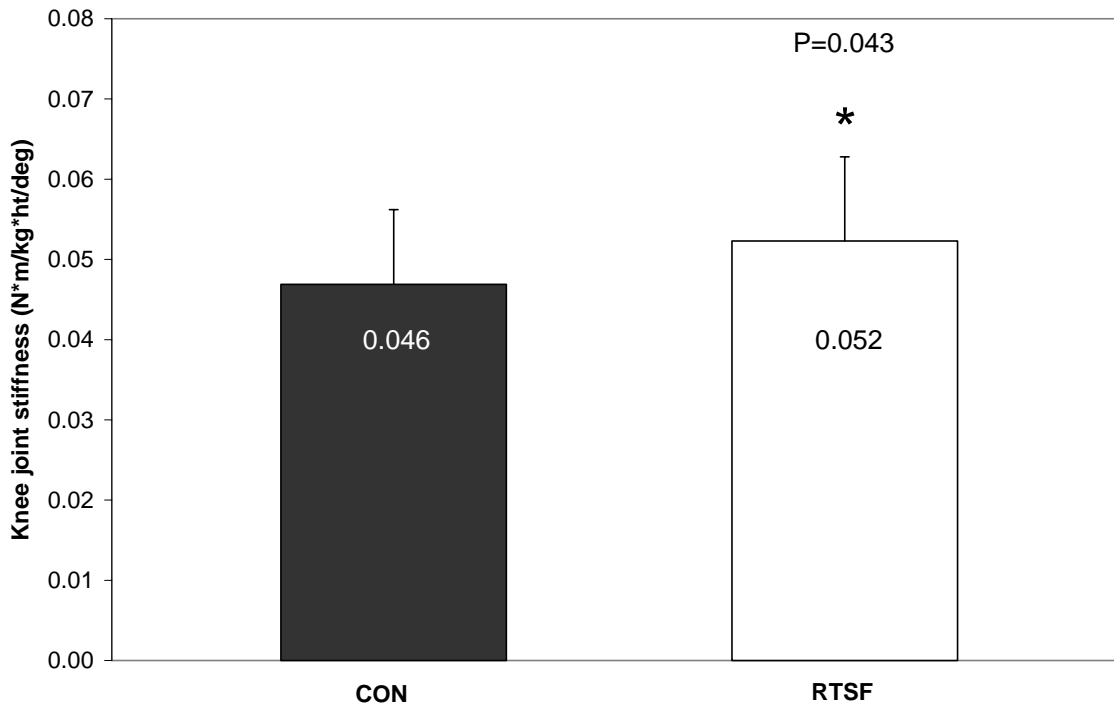


Figure 4: Average sagittal plane knee joint stiffness in subjects who had a previous tibial stress fracture versus healthy controls (* = significantly greater than controls).

Hypothesis 1.2: Runners who had sustained a previous TSF would exhibit differences in kinematic variables including increased peak positive tibial acceleration, decreased ankle dorsiflexion excursion and decreased knee flexion excursion compared to controls.

Subjects who had sustained a previous tibial stress fracture exhibited significantly greater peak positive tibial acceleration than control subjects. There was no difference in ankle dorsiflexion excursion between the two groups. Knee joint excursion was reduced in the TSF group, and this change was reflected in an increase in knee joint stiffness in these runners. A “stiff” runner will spend less time in contact with the ground (Farley and Gonzalez, 1996) and will attenuate less shock between the leg and the head (McMahon et al., 1987). This is in agreement with the findings of Farley and Gonzalez (1996) who suggested lower extremity stiffness and knee flexion excursion are highly correlated and may lead to stress fracture.

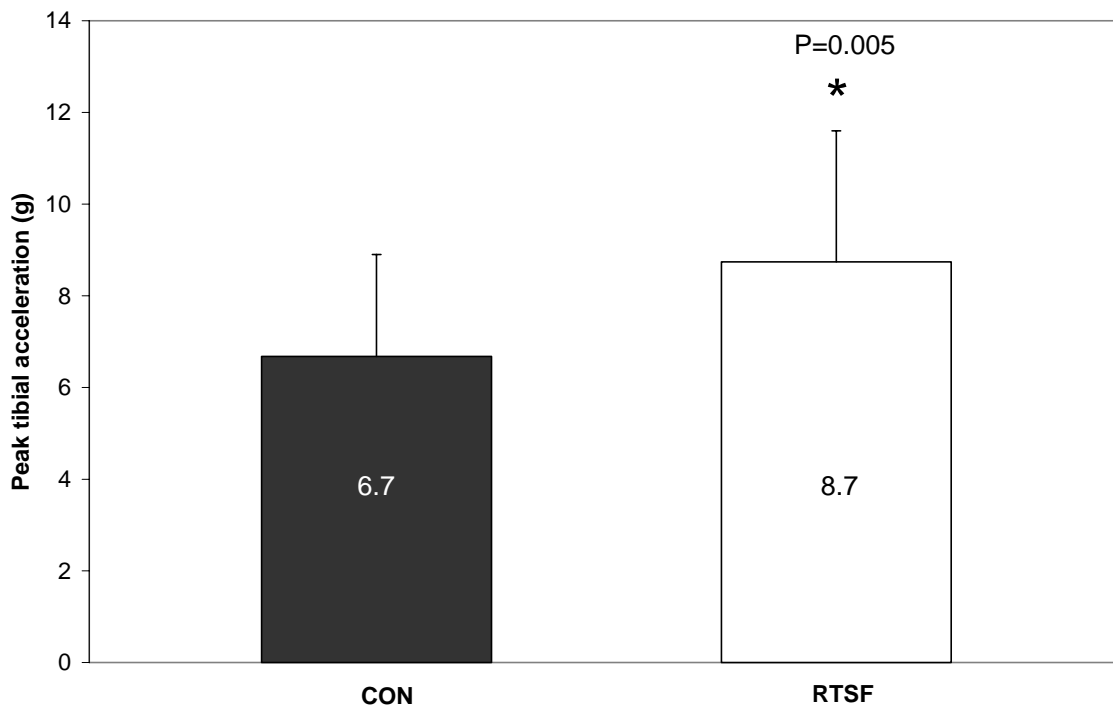


Figure 5: Peak positive tibial acceleration in subjects who had a previous tibial stress fracture versus healthy controls (* = significantly greater than controls).

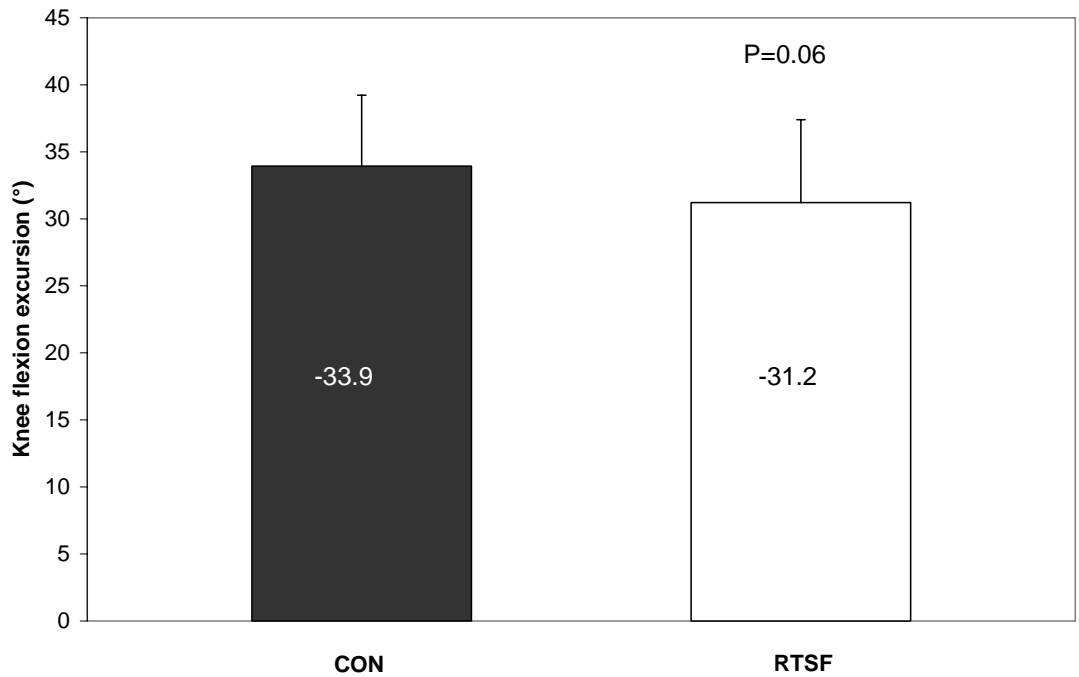


Figure 6: Knee flexion excursion in subjects who had a previous tibial stress fracture versus healthy controls (* = significantly less than controls).

Hypothesis 1.3: Runners who had sustained a previous TSF would exhibit differences in structural variables including increased tibial varum and decreased tibial area moment of inertia compared to healthy controls.

Although specific structural characteristics have been associated with stress fracture injuries in male runners (Crossley et al., 1999; Milgrom et al., 1989), these groups of female distance runners did not demonstrate this relationship. No difference in tibial area moment of inertia or tibial varum was observed between the two groups (Table 2). These data are in agreement with recent work by Bennell et al. (2004), who found no difference in tibial bone geometry between female runners with and without a history of tibial stress fracture.

Table 2: Variables that showed no difference between subjects who had a previous tibial stress fracture and healthy controls.

	RTSF	CON	P value
Ankle dorsiflexion excursion	20.60 ± 5.48	22.09 ± 4.07	0.15
Peak vertical force (BW)	2.51 ± 0.19	2.53 ± 0.15	0.34
Impact peak (BW)	1.85 ± 0.19	1.77 ± 0.34	0.15
Peak braking force (BW)	-0.40 ± 0.07	-0.39 ± 0.05	0.34
Instantaneous braking load rate (BW/s)	21.93 ± 7.29	20.95 ± 5.36	0.30
Leg stiffness (kN/m)	8.78 ± 1.55	9.07 ± 1.49	0.28
Ankle jt stiffness (Nm/mass*ht ^o)	0.33 ± 0.35	0.29 ± 0.38	0.36
Area moment of inertia (mm ⁴)	11403 ± 3224	12507 ± 3813	0.20
Tibial varum (°)	5.71 ± 2.31	6.43 ± 1.59	0.11

The observed decreases in knee joint excursion suggest that stiffness would be increased in the RTSF group. This was supported by the measure of knee joint stiffness that was included in this analysis, but not by the global measure of vertical leg stiffness. It appears that the stiffness of the individual joints, may be a more sensitive measure than the simple global measure employed initially. The observed increases in vertical loading rate and tibial acceleration support the notion that these impact-related kinetic variables may be related to the risk of tibial stress fracture. Additionally, the increase in average loading rate during braking suggests that this secondary plane may be of some importance in relation to tibial stress fracture.

There were no differences in tibial area moment of inertia between the RTSF and control groups. This is contrary to the study by Milgrom et al. (1989) who found a highly significant reduction in tibial area moment of inertia in the recruits who sustained a tibial stress fracture. However, they studied male military recruits compared to female runners examined in our study. The lack of a significant difference between the RTSF and control groups in this preliminary analysis suggests that other factors may be important in the etiology of tibial stress fractures in the female running population. Overall, area moment of inertia values in the RTSF group were 20% less than those reported by Milgrom et al. (1989). However, this is due to the smaller tibial width of females, which is correlated strongly with tibial area moment of inertia. Furthermore, the recent work by Bennell et al. (2004) suggests that these structural differences are not present in groups of female runners with and without a history of tibial stress fracture.

It should be noted that the kinetic differences between the RTSF and control groups are similar to those reported for the smaller group (n=20) of subjects that was considered two years ago. This year, our understanding of the differences between the groups has been enhanced by the inclusion of several extra stiffness and ground reaction force variables. These variables were included based on trends that we have observed in the data over the past year. We are continuing to refine our analysis by analyzing other variables during the first 50 ms of stance.

2) Summary of the prospective data obtained on female runners who sustained a tibial stress fracture during the study

Aim 2: Determine whether differences in structure and mechanics exist between subjects who sustain a tibial stress fracture (PTSF) to those who do not sustain a fracture.

Currently, only a relatively small number of participants have experienced tibial stress fractures (8 fractures in 6 subjects) during the follow-up period of the study. As advised by the reviewers of last year's report, we have analyzed PTSF data separately from tibial stress reactions. The PTSF group was compared to an age and mileage-matched control group (Table 3).

Table 3: Mean (\pm standard deviation) monthly running mileage and age of the PTSF and CON groups

	Mileage (miles/ month)	Age (years)
PTSF (n=6)	79 \pm 30	21 \pm 4
CON (n=6)	89 \pm 13	26 \pm 10

Hypothesis 2.1: Runners who sustained a TSF would exhibit differences in kinetic variables including increased instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to controls.

Due to the small number of subjects in each group, statistical analyses of these data were not conducted. Instead, we have operationally defined a difference of 15% between the groups as indicating a clinically significant difference. In this group of PTSF subjects, we found several differences in comparison to the matched control group. As expected, impact peak (Fig. 7) and instantaneous loading rate (Fig. 8) were higher in the PTSF group. However, loading rates during braking (Figs. 9 and 10) were lower in the PTSF group compared to controls. These lower values in the PTSF group were contrary to our hypotheses and to our retrospective data. However, these preliminary results from the TSFs sustained during the study should be interpreted cautiously, since the number of subjects involved is small.

Due to the small number of subjects involved, these data are sensitive to the specific subjects sampled and can change noticeably with the addition or exclusion of even one individual's data. As the number of subjects with prospective TSF increases, this problem should diminish.

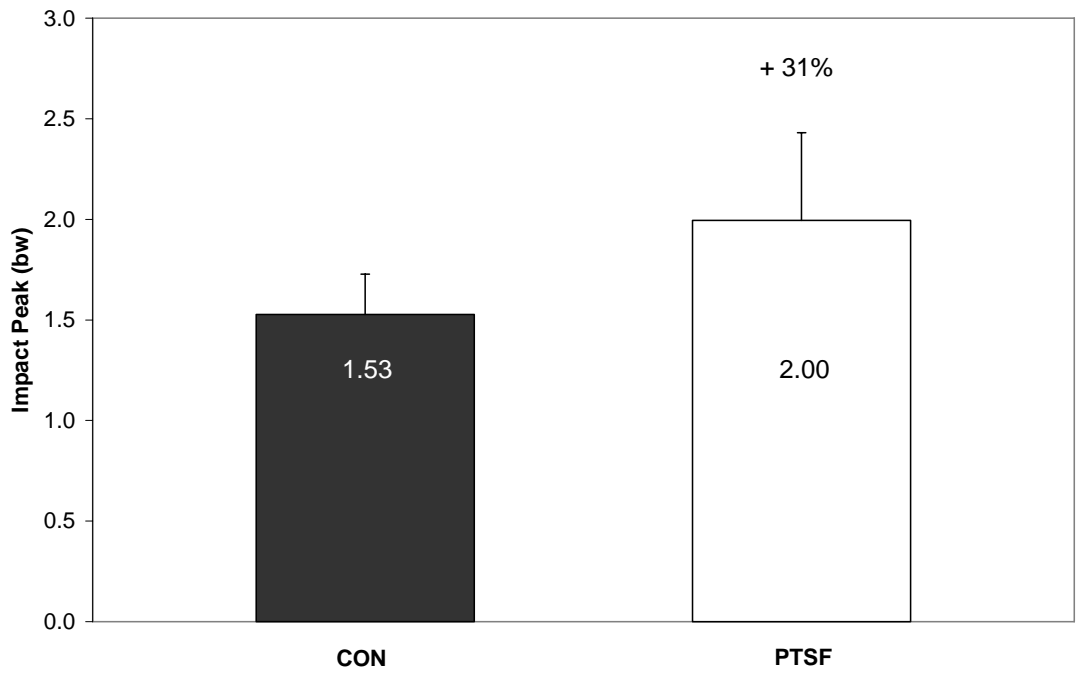


Figure 7: Impact peak during braking in subjects who developed a tibial stress fracture versus healthy controls.

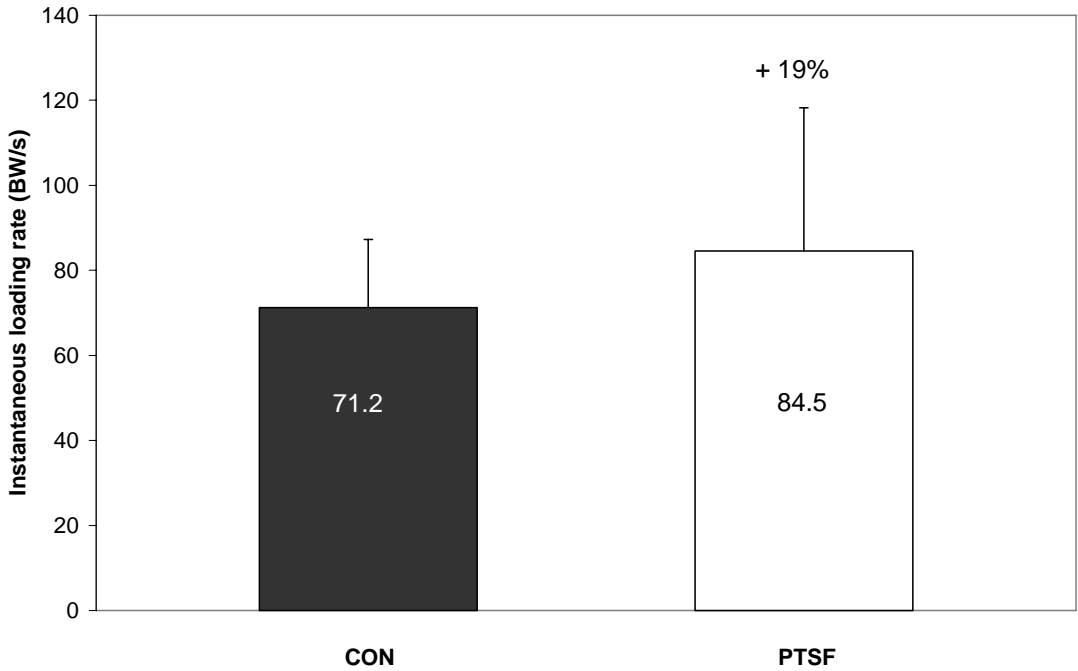


Figure 8: Instantaneous loading rate during braking in subjects who developed a tibial stress fracture versus healthy controls.

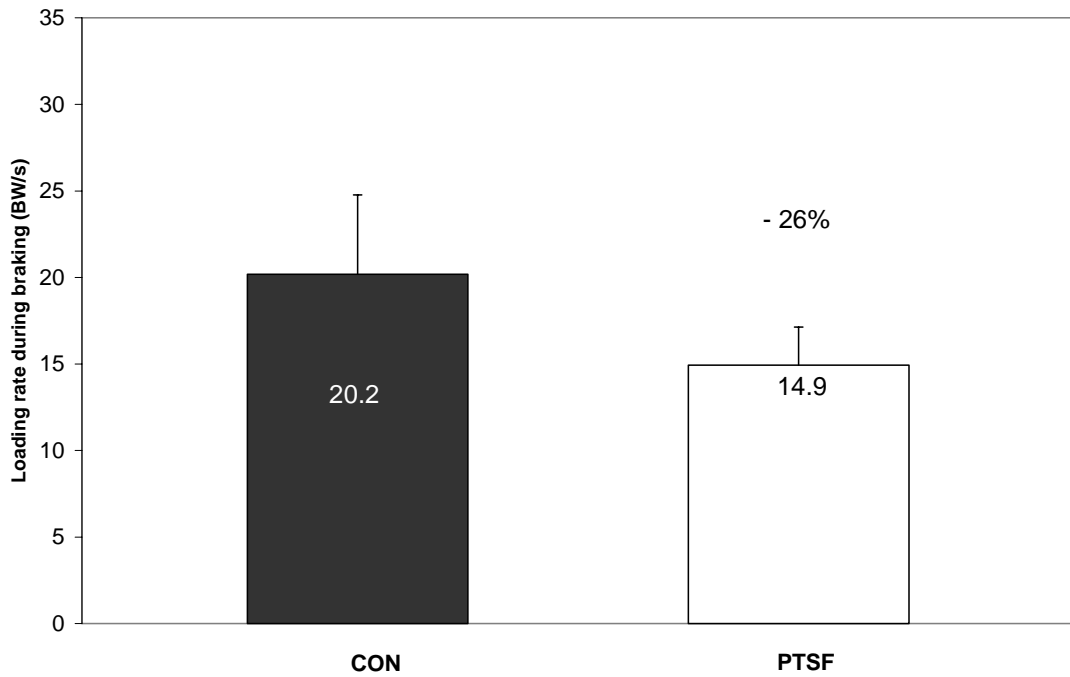


Figure 9: Instantaneous loading rate during braking in subjects who developed a tibial stress fracture versus healthy controls.

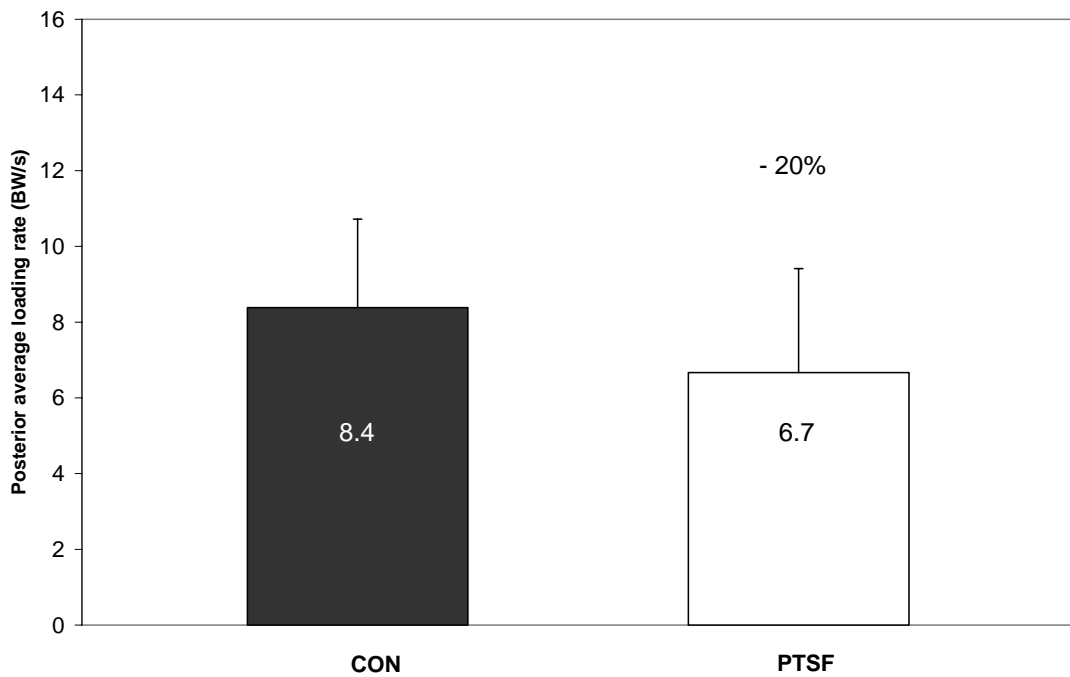


Figure 10: Average loading rate during braking in subjects who developed a tibial stress fracture versus healthy controls.

Hypothesis 2.2: Runners who sustained a PTSF would exhibit differences in kinematic variables including increased peak positive tibial acceleration, decreased ankle dorsiflexion excursion and decreased knee flexion excursion compared to controls.

The prospective TSF group exhibited no difference in these variables compared to the healthy controls (Table 4). This differs from the retrospective TSF group, which had reduced knee flexion excursion and tibial acceleration compared to the control group. In addition, there were some individuals within the PTSF group who had excessively high values. For example, two PTSF subjects had tibial shock value over 9g, higher than the mean value for the RTSF group. These same two subjects also had instantaneous vertical loading rates over 100 BW/s, also higher than the average of the RTSF group. Although they did not meet the criteria of 15% difference, it should be noted that PPA (shock) was 8% higher, average vertical loading rates were 13% higher and knee stiffness was 12% higher in the PTSF group as expected.

Hypothesis 2.3: Runners who sustained a PTSF would exhibit differences in structural variables including increased tibial varum and decreased tibial area moment of inertia compared to healthy controls.

Tibial varum was 20% lower in the prospective TSF group compared to the healthy controls (Fig. 11).

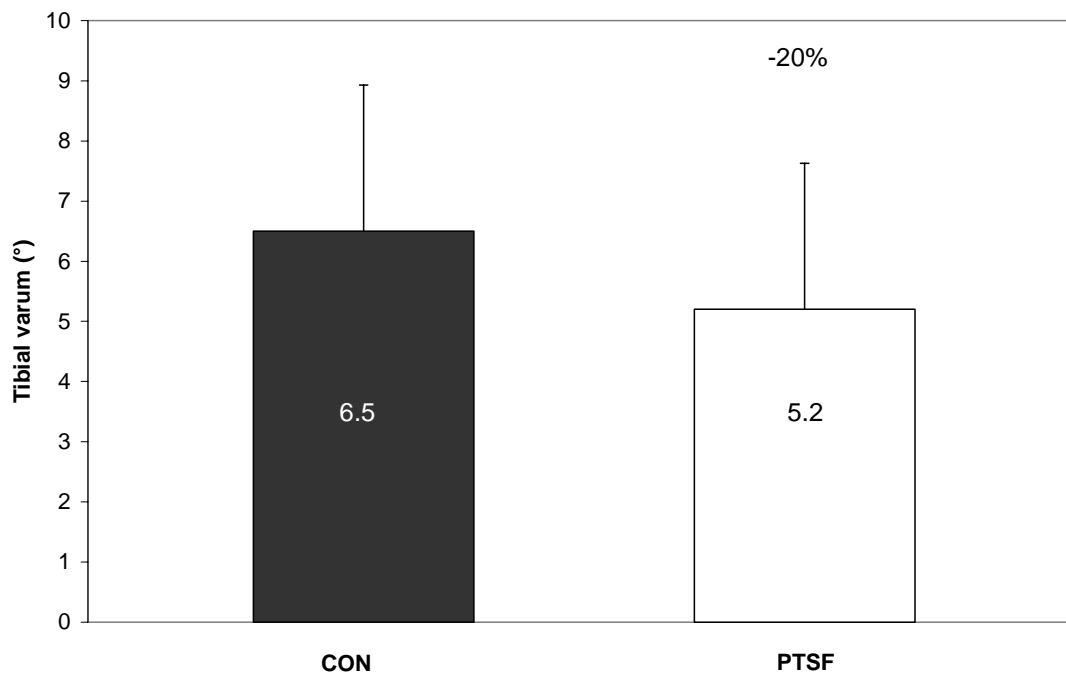


Figure 11: Tibial varum in subjects who developed a tibial stress fracture versus healthy controls.

Table 4: Variables that showed no difference between subjects who had a prospective tibial stress fracture and healthy controls.

	PTSF	CON	% diff.
Peak vertical force (BW)	2.54 ± 0.11	2.60 ± 0.11	-2.4
Average vertical load rate (BW/s)	70.66 ± 33.95	62.21 ± 12.60	13.6
Peak positive tibial acceleration (g)	6.42 ± 3.30	5.94 ± 0.92	8.1
Peak braking force (BW)	-0.35 ± 0.05	-0.38 ± 0.06	-8.2
Leg stiffness	7.99 ± 0.86	9.26 ± 1.66	-13.7
Ankle joint stiffness (Nm/mass*ht ^o)	0.045 ± 0.012	0.045 ± 0.005	-1.3
Knee joint stiffness (Nm/mass*ht ^o)	0.045 ± 0.015	0.041 ± 0.005	11.8
Ankle dorsiflexion excursion (°)	20.7 ± 3.0	22.0 ± 2.1	-5.7
Knee flexion excursion (°)	35.3 ± 4.2	36.6 ± 3.9	-3.5
Area moment of inertia (mm ⁴)	10,963 ± 942	11,788 ± 2,316	-7.0

In conclusion, the limited amount of data so far available for prospective tibial stress fractures partially reflects differences observed in the retrospective tibial stress fracture group. However, results suggest that differences, though not yet significant, are in the expected direction. As statistical power increases with additional prospective fractures, it is hoped that these differences will become more clear.

3) Summary of the prospective data obtained on ALL of the lower extremity stress fractures: comparison to uninjured female runners

Aim 3: Determine whether differences in structure and mechanics exist between subjects who sustain a lower extremity fracture (PSF) to those who do not sustain a fracture.

Due to the small number of participants who have experienced a TSF, we also analyzed all prospective stress fracture injuries combined (6 TSF, 8 femoral, 1 pelvic, 2 fibular, 5 metatarsal).

Table 5: Mean (± standard deviation) monthly running mileage and age of the PSF and CON groups

	Mileage (miles/ month)	Age (years)
PSF (n=22)	101 ± 39	26 ± 9
CON (n=22)	107 ± 28	27 ± 10

Hypothesis 3.1: Runners who sustained a PSF would exhibit differences in kinetic variables including increased instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to controls.

Similar differences between the PSF and control group were found as were observed in the PTSF group alone. A trend toward a higher vertical impact peak and instantaneous loading rate in the PSF group reflected that found in the PTSF group (Figs. 12 and 13).

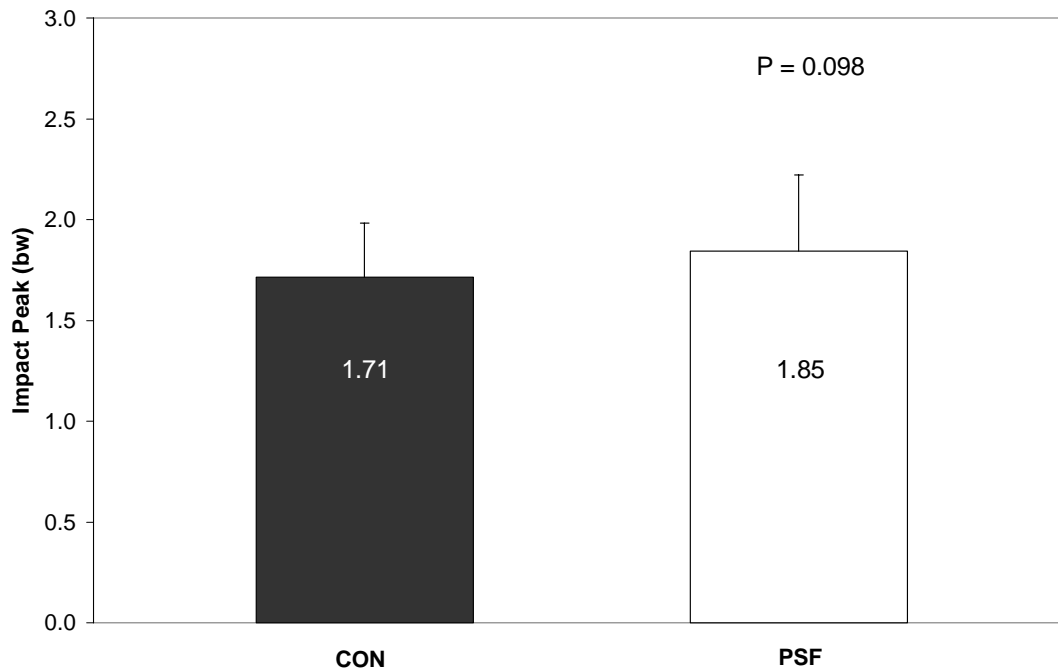


Figure 12: Impact peak in subjects who developed a stress fracture versus healthy controls.

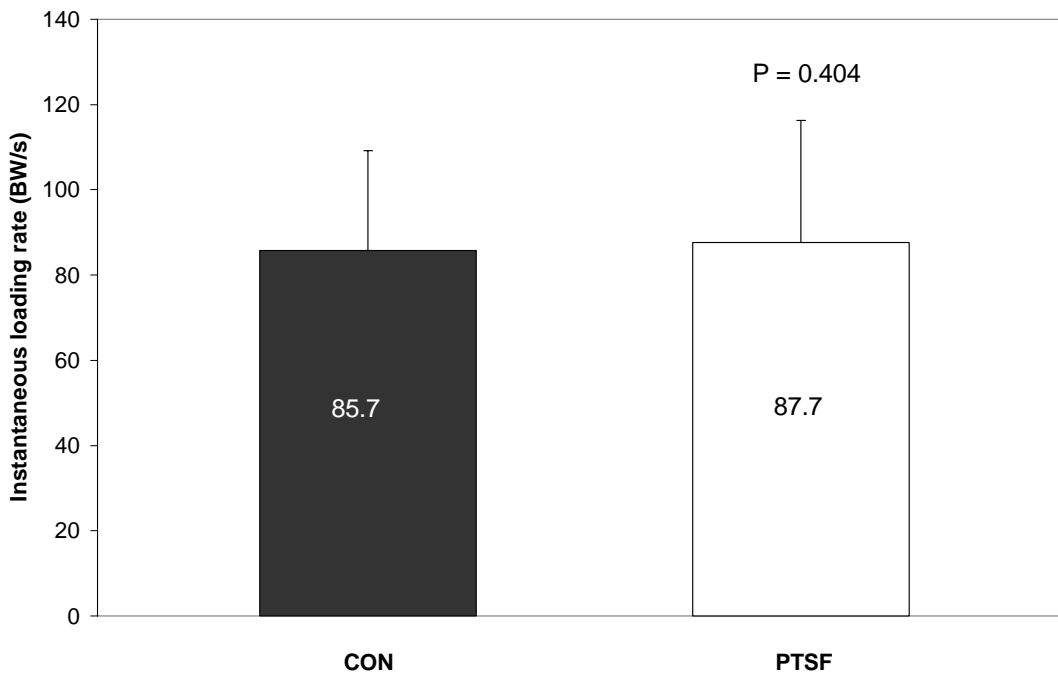


Figure 13: Instantaneous vertical loading rate in subjects who developed a stress fracture versus healthy controls.

Hypothesis 3.2: Runners who sustained a PSF would exhibit differences in kinematic variables including increased peak positive tibial acceleration, decreased ankle dorsiflexion excursion and decreased knee flexion excursion compared to controls.

Ankle dorsiflexion and knee flexion excursion showed a trend towards being significantly lower in the PSF group compared to controls, as expected (Figs. 14 and 15). This suggests that stiffness might be higher in these joints, however that is not the case as of yet. While not statistically significant, PPA was 10% higher in the runners who developed a Lower extremity stress fracture (Table 6).

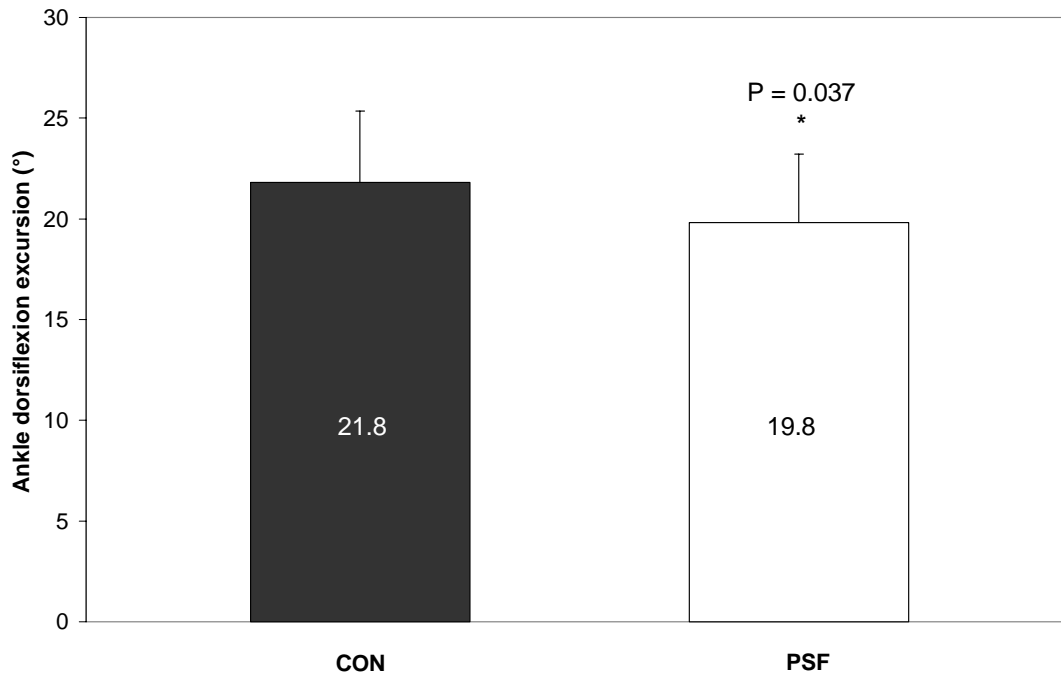


Figure 14: Ankle dorsiflexion excursion in subjects who developed a stress fracture versus healthy controls.

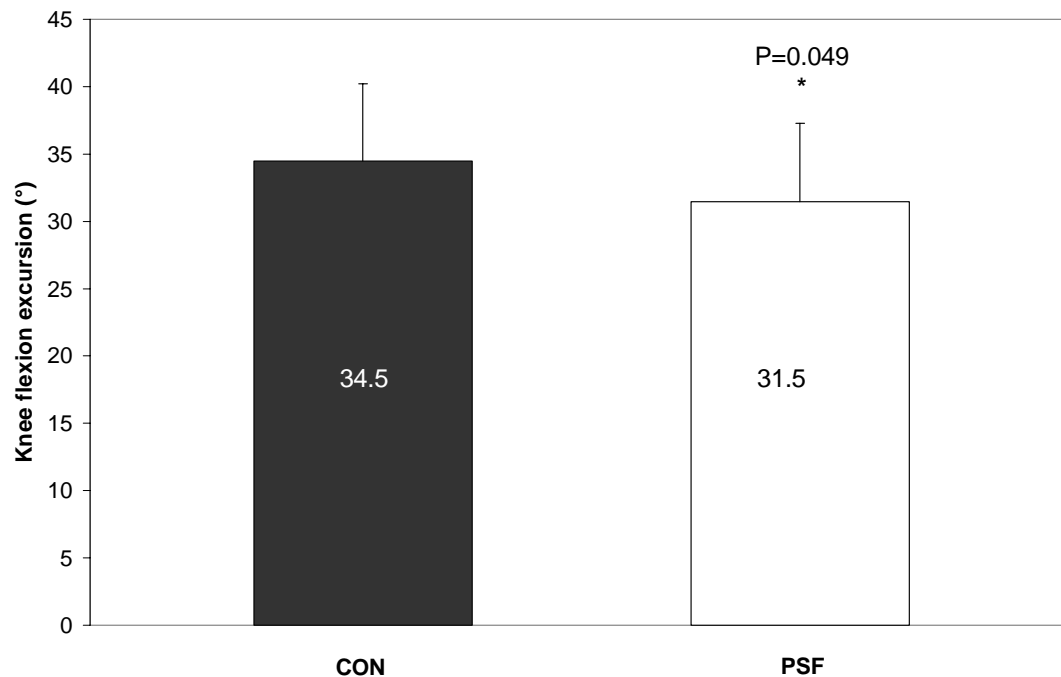


Figure 15: Knee flexion excursion in subjects who developed a stress fracture versus healthy controls.

Hypothesis 3.3: Runners who sustained a PSF would exhibit differences in structural variables including increased tibial varum and decreased tibial area moment of inertia compared to healthy controls.

This group of PSF subjects demonstrated a 31% decrease in tibial varum, which is opposite to what we expected, but also found in the PTSF group (Fig. 16). We expected that greater tibial varum would be associated with stress fractures (especially tibial) secondary to the increased bending moment on the leg.

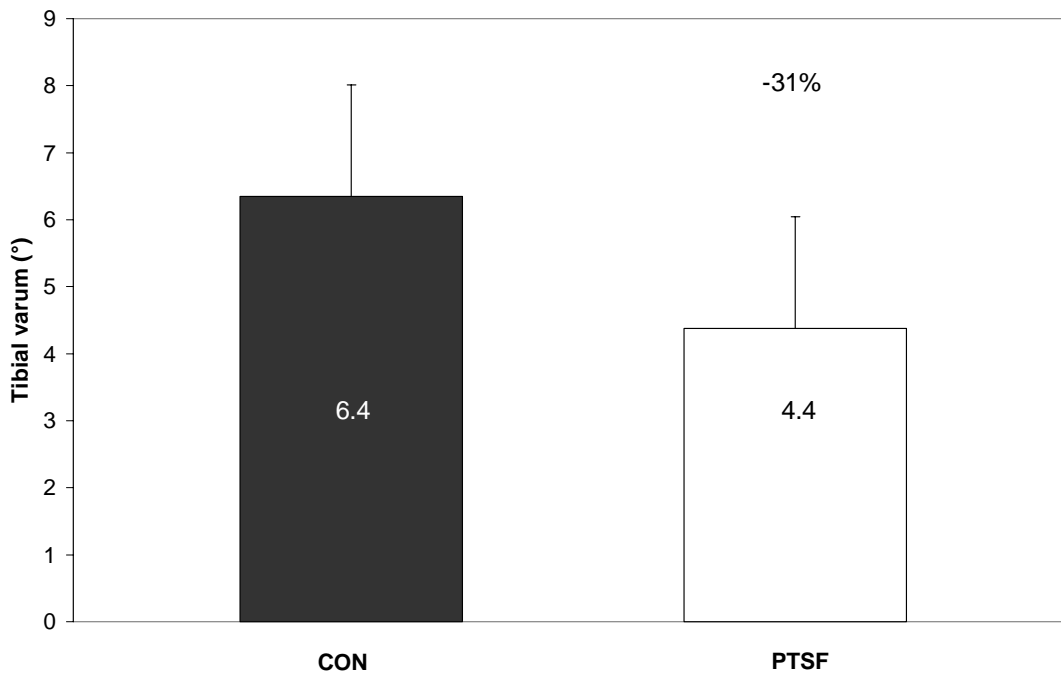


Figure 16: Tibial varum in subjects who developed a lower extremity stress fracture versus healthy controls.

Table 6: Variables that showed no difference between subjects who had a prospective stress fracture and healthy controls.

	PSF	CON	P value
Peak vertical force (BW)	2.48 ± 0.18	2.54 ± 0.15	#
Average vertical loading rate (BW/s)	74.22 ± 27.49	73.07 ± 22.38	0.441
Peak braking force (BW)	-0.36 ± 0.09	-0.39 ± 0.06	#
Braking instantaneous load rate (BW/s)	20.5 ± 8.6	23.5 ± 6.79	#
Braking average load rate (BW/s)	7.37 ± 2.67	8.93 ± 5.2	#
Peak tibial acceleration	6.34 ± 3.83	5.75 ± 2.96	0.290
Vertical leg stiffness (kN/m)	7.84 ± 1.09	8.57 ± 1.43	#
Ankle joint stiffness (Nm/mass*ht/°)	0.042 ± 0.012	0.047 ± 0.005	#
Knee joint stiffness (Nm/mass*ht/°)	0.043 ± 0.013	0.045 ± 0.009	#
Tibial area moment of inertia	12,222 ± 1,919	12,062 ± 2441	#

indicates that the difference between groups was in the opposite direction to the hypothesis. Use of the one-tailed t-test precludes interpretation of these data.

4) Summary of pre and post injury data from six individuals with prospective tibial stress fractures

Aim 4: Compare mechanics of individuals with healed tibial stress fractures to their mechanics prior to the fracture to determine whether compensation for injury occurs. As advised by the reviewers of last year’s report, we have not included tibial stress reactions in this comparison (last year we reported on 4 TSFs and 4 TSRs). We consider group differences of 15% or more to be clinically significant. With the addition of more subjects in the future, statistical analysis will be performed.

Hypothesis 4.1: Runners with healed TSFs would not exhibit changes in kinetic variables including instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to their pre-injury status.

Table 7: Mean kinetic variables for six prospective tibial stress fracture subjects pre and post injury.

	PRE	POST	% Difference
Impact peak (BW)	2.00 ± -0.44	2.01 ± 0.39	0.8
Peak vertical force (BW)	2.54 ± 0.11	2.48 ± 0.19	-2.4
Vertical instantaneous load rate (BW/s)	84.54 ± 33.71	79.05 ± 36.29	-6.5
Vertical average load rate (BW/s)	70.66 ± 33.95	63.58 ± 38.71	-10.0
Peak braking force (BW)	-0.35 ± 0.05	-0.36 ± 0.05	4.9
Vertical leg stiffness (kN/m)	7.99 ± 0.86	7.94 ± 0.80	-0.6
Ankle joint stiffness (Nm/mass*ht ³)	0.042 ± 0.005	0.045 ± 0.006	8.7

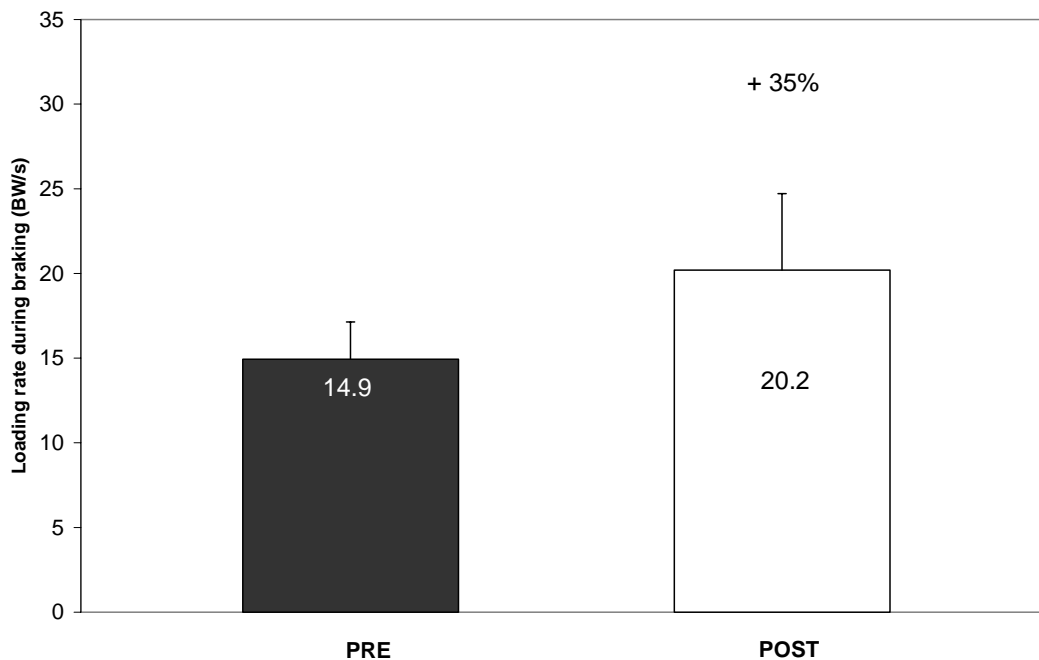


Figure 17: Instantaneous loading rate during braking pre and post tibial stress fracture.

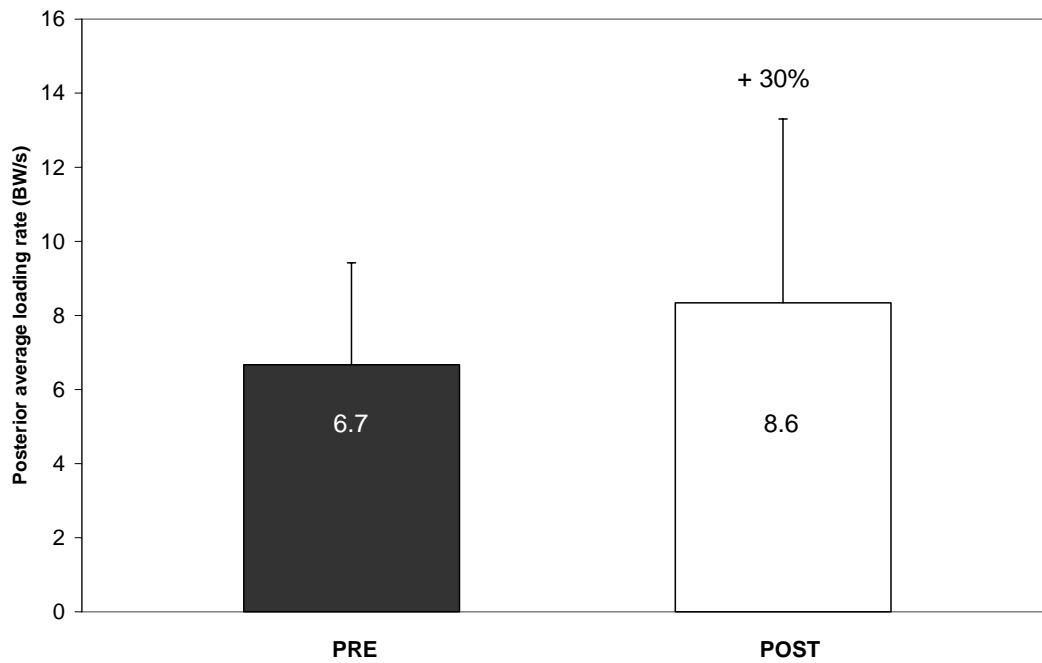


Figure 18: Average loading rate during braking pre and post tibial stress fracture.

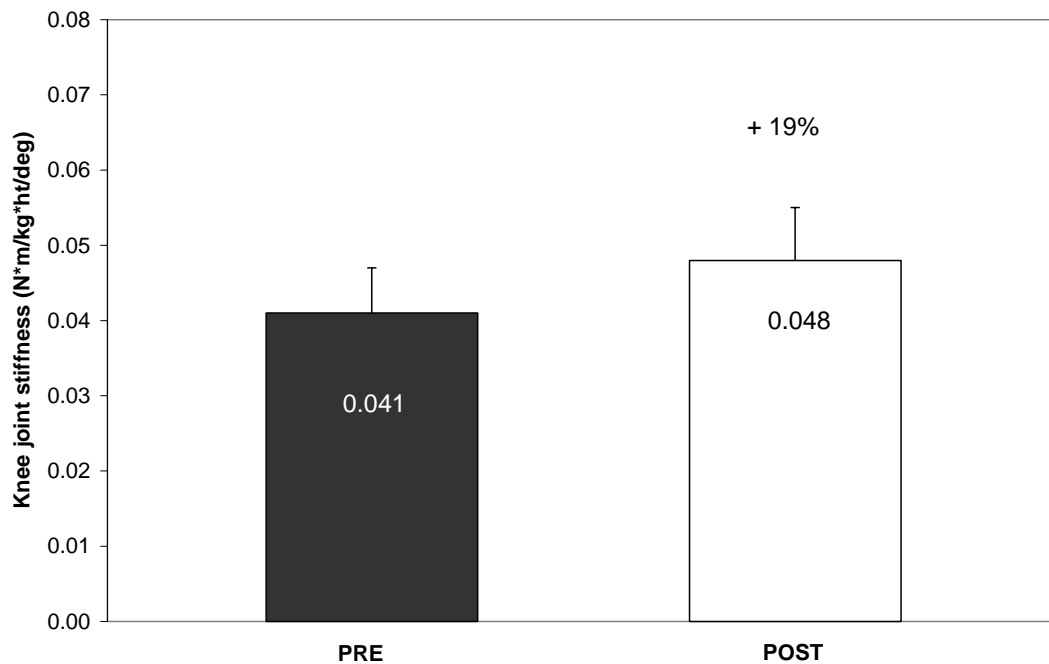


Figure 19: Knee joint stiffness pre and post tibial stress fracture.

At this stage, there are only minimal differences between pre and post injury kinetic variables for runners who sustained a TSF during the study, with the exception of loading rates during braking. Both instantaneous and average loading rates during braking were increased at the post- injury visit. These shear loading rates indicate the magnitude of bending loads that the lower extremity is subject to, in addition to the compressive loading that occurs during initial weight acceptance in stance. It has been

shown that anterior-posterior bending strength is related to the risk of tibial stress fracture (Milgrom et al., 1989). Therefore, the magnitude of anterior-posterior loading rates may be directly related to stress fracture. The secondary planes of ground reaction force are often overlooked in gait analyses, but these substantial changes indicate that they are worthy of further investigation in relation to stress fracture injuries in runners. An increase in knee joint stiffness is also apparent, which may contribute to an increased injury risk.

Hypothesis 4.2: Runners with healed TSFs would not exhibit changes in kinematic variables including peak tibial acceleration, ankle dorsiflexion excursion and knee flexion excursion compared to their pre-injury status.

Table 8: Mean kinematic variables for six prospective tibial stress fracture subjects pre and post injury.

	PRE	POST	% Difference
Peak tibial acceleration (g)	6.48 ± 3.23	7.04 ± 3.07	8.6
Ankle dorsiflexion excursion (°)	20.7 ± 3.0	20.4 ± 1.5	-1.4
Knee flexion excursion (°)	35.3 ± 4.2	33.9 ± 2.8	-4.0

Furthermore, a small increase in tibial shock occurred following recovery from injury. Since stress fractures are essentially fatigue fractures of the bone, their occurrence relates to the load per cycle and the number of cycles. Increasing either of these factors increases the risk of exceeding the fatigue limit of the tissue. Both loading rates during braking and tibial shock indicate the magnitude of compression loading per cycle, therefore higher values indicate increased risk.

These data suggest that there may be some changes in the gait of runners who sustain a stress fracture following recovery from the fracture. There are increases in several loading related variables, which may help to explain the 36% incidence of reinjury following a lower extremity stress fracture in runners.

Due to the low numbers, these data provide only a suggestion of the changes that may occur following recovery from such an injury. As more tibial stress fractures occur in the study population, statistical analysis of the changes will be carried out to determine whether there is a change between pre and post tibial stress fracture mechanics. If mechanics associated with stress fractures either remain the same or increase once the stress fracture is healed, there is a need to address these abnormal mechanics. We have begun to develop a gait retraining program aimed at reducing loads associated with runners at risk.

If these findings are seen consistently as additional subjects are added, there may be a need to retrain the gait patterns of runners who sustain tibial stress fractures, to reduce the risk of recurring fractures. In addition, if differences between pre and post injury mechanics persist, this provides further support of the need for prospective studies.

5) Summary of pre and post injury data from all prospective lower extremity stress fractures

Aim 5: Compare mechanics of individuals with healed lower extremity stress fractures to their mechanics prior to the fracture to determine whether compensation for injury occurs. This group comprises 1 pelvic, 3 femoral, 6 tibial and 2 metatarsal stress fractures.

With the relatively small number of participants who have experienced tibial stress fractures prospectively and returned for a reassessment, we have extended this comparison to include all lower

extremity stress fractures. Again, we consider group changes of 15% or more to be clinically significant. With the addition of more subjects in the future, statistical analysis will be performed.

Hypothesis 4.1: Runners with healed SFs would not exhibit changes in kinetic variables including instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to their pre-injury status.

Table 9: Mean kinetic variables for 12 prospective lower extremity stress fracture subjects pre and post injury.

	PRE	POST	% Difference
Impact peak (BW)	1.92 ± 0.37	2.00 ± 0.40	4.4
Peak vertical force (BW)	2.41 ± 0.23	2.44 ± 0.25	1.3
Vertical instantaneous load rate (BW/s)	87.31 ± 29.84	86.39 ± 38.55	-1.0
Vertical average load rate (BW/s)	73.57 ± 29.49	71.74 ± 37.97	-2.5
Peak braking force (BW)	-0.35 ± 0.08	-0.38 ± 0.09	6.9
Braking average load rate (BW/s)	7.36 ± 2.57	8.17 ± 3.90	11.0
Vertical leg stiffness (kN/m)	8.70 ± 3.09	7.71 ± 0.85	-11.4
Ankle joint stiffness (Nm/mass*ht ³)	0.040 ± 0.013	0.046 ± 0.005	13.9

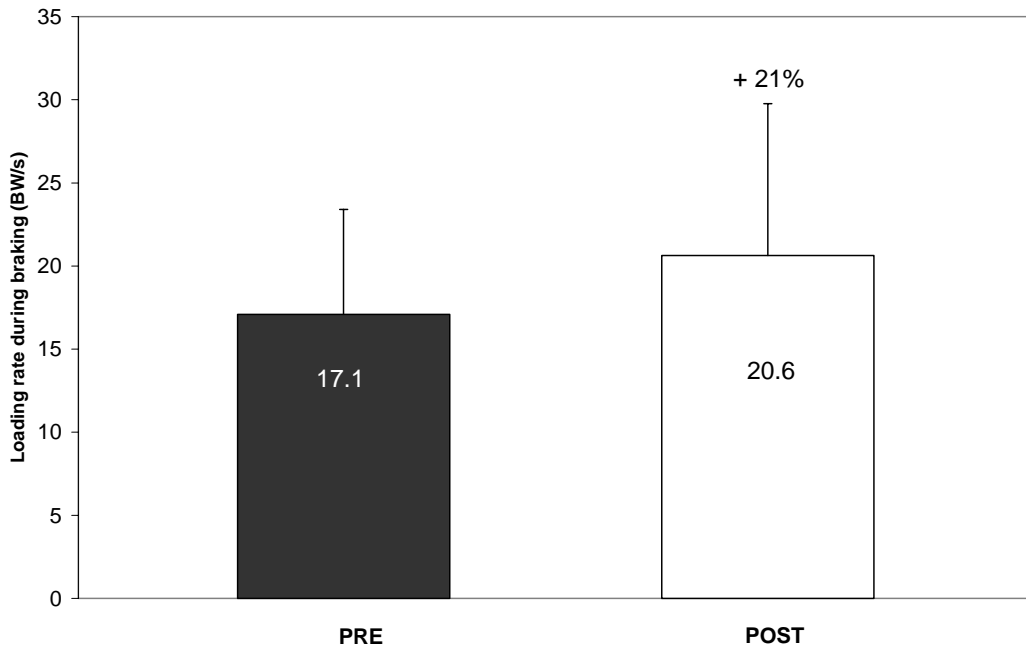


Figure 20: Instantaneous loading rate during braking pre and post lower extremity stress fracture.

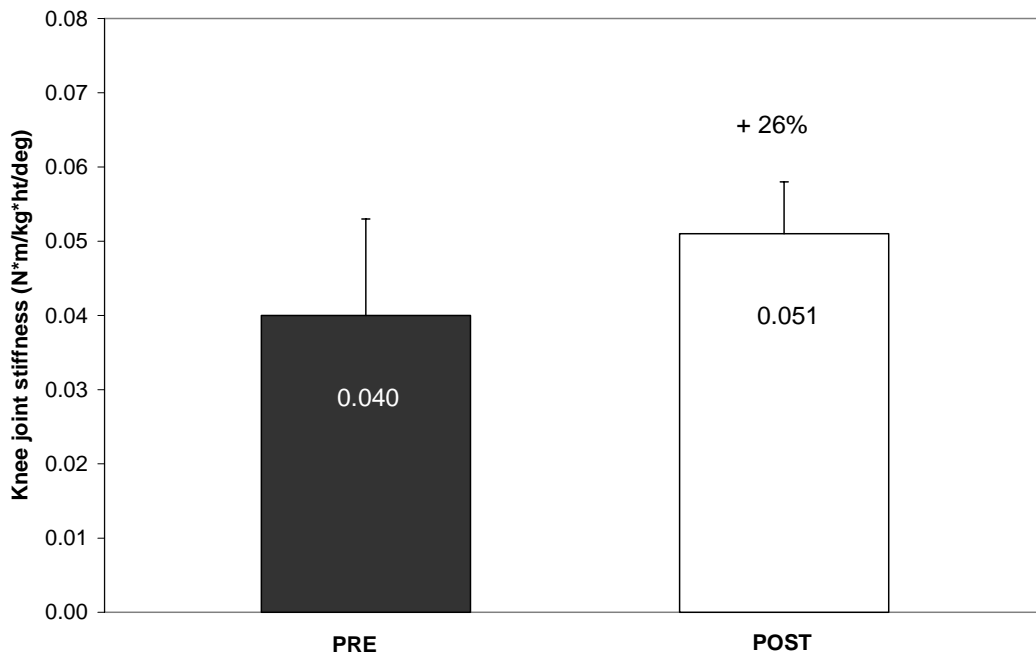


Figure 21: Knee joint stiffness pre and post lower extremity stress fracture.

Similar to the PTSF data, responses are variable. However, there was a general trend of increased anteroposterior loading rates during braking in this group, but not vertical loading characteristics. Increases in ankle and knee joint stiffness are also apparent post stress fracture, again reflecting changes observed in the PTSF group.

Hypothesis 4.2: Runners with healed SFs would not exhibit changes in kinematic variables including peak tibial acceleration, ankle dorsiflexion excursion and knee flexion excursion compared to their pre-injury status.

Table 10: Mean kinematic variables for 12 prospective lower extremity stress fracture subjects pre and post injury.

	PRE	POST	% Difference
Peak tibial acceleration (g)	7.67 ± 4.21	7.90 ± 3.53	2.9
Ankle dorsiflexion excursion (°)	20.9 ± 2.8	20.8 ± 1.8	0.0
Knee flexion excursion (°)	32.0 ± 6.5	31.8 ± 4.7	-0.5

No changes were noted in these variables.

6) Summary of the prospective data obtained on female runners who sustained a tibial stress reaction during the study

Determine whether differences in structure and mechanics exist between subjects who sustain a tibial stress reaction (PTSR) to those who do not sustain a fracture.

Tibial stress reactions have been operationally defined as bony pain specifically along the distribution of the tibia that is worsened with impact loading and relieved with rest. There is indication in the literature (Fredericson et al., 1995) that these stress reactions are the early stage of a stress fracture. As advised by

the reviewers of last year's report, we have not pooled the PTSF data with data from tibial stress reactions, however we feel that this group represents a precursor to tibial stress fracture and, therefore have included it here. The PTSR group (13 TSR in 8 individuals) was compared to the control group used in comparison to PTSF.

Runners who sustained a PTSR would exhibit differences in kinetic variables including increased instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to controls.

Due to the small number of subjects in each group (n=8), statistical analyses of these data were not conducted. Instead, we have operationally defined a difference of 15% between the groups as indicating a clinically significant difference. In this group of PTSR subjects, we found several differences in comparison to the matched control group. As expected, impact peak and instantaneous loading rate were higher in the PTSR group (Table 11). However, instantaneous loading rate during braking was lower in the PTSR group compared to controls. This lower value in the PTSR group was contrary to our hypothesis. These preliminary results from the TSRs sustained during the study should be interpreted cautiously, since the number of subjects involved is small.

Due to the small number of subjects involved, these data are sensitive to the specific subjects sampled and can change noticeably with the addition or exclusion of even one individual's data.

Runners who sustained a PTSR would exhibit differences in kinematic variables including increased peak positive tibial acceleration, decreased ankle dorsiflexion excursion and decreased knee flexion excursion compared to controls.

The prospective TSR group exhibited increased tibial acceleration compared to the healthy controls. This is in partial agreement with the retrospective TSF group, which had reduced knee flexion excursion and tibial acceleration compared to the control group.

Runners who sustained a PTSR would exhibit differences in structural variables including increased tibial varum and decreased tibial area moment of inertia compared to healthy controls.

Tibial varum was unexpectedly lower (by 34%) in the prospective TSR group compared to the healthy controls.

Table 11: Kinetic variables between subjects who had a prospective tibial stress reaction and healthy controls.

	PTSF	CON	% diff.
Impact peak (BW)	1.76 ± 0.38	1.64 ± 0.34	7.3
Peak vertical force (BW)	2.45 ± 0.19	2.63 ± 0.17	-6.8
Average vertical load rate (BW/s)	69.61 ± 27.35	70.05 ± 18.61	-0.6
Instantaneous vertical load rate (BW/s)	80.65 ± 26.00	79.15 ± 20.83	1.9
Peak positive tibial acceleration (g)	6.99 ± 4.17	6.06 ± 1.79	15.3
Peak braking force (BW)	-0.34 ± 0.13	-0.40 ± 0.06	-14.9
Average braking load rate (BW/s)	9.21 ± 3.40	10.53 ± 6.92	-12.6
Instantaneous braking load rate (BW/s)	16.00 ± 5.65	21.96 ± 6.08	-27.1
Leg stiffness	7.74 ± 1.19	9.18 ± 1.87	-15.7
Ankle dorsiflexion excursion (°)	20.1 ± 3.2	21.5 ± 2.0	-6.7
Knee flexion excursion (°)	35.1 ± 3.4	33.9 ± 3.5	3.7
Tibial varum (°)	4.3 ± 1.7	6.5 ± 2.4	-34.1
Area moment of inertia (mm ⁴)	12424 ± 2188	11788 ± 2316	5.4

In conclusion, the limited amount of data so far available for prospective tibial stress reactions only partially reflects differences observed in the retrospective tibial stress fracture group. Differences were found in ground reaction force variables, in both the same and opposite direction as found in the retrospective groups. This may partly be a consequence of the small subject group. By concentrating our final recruitment on high risk groups, we hope to have more occurrences of prospective tibial stress fracture in the next 12 month period. This will enable us to compare a larger group to uninjured controls, to try and elucidate pre-existing differences between runners who sustain a tibial stress fracture and those who do not.

7) List of Publications

Since the last report, three manuscripts have been accepted for publication in peer-reviewed journals. One has been published in *Medicine and Science in Sports and Exercise*, the second is in press with *Journal of Biomechanics*. A third manuscript in relation to gait retraining has been published in *Orthopedic Physical Therapy Practise*. These articles are included in Appendix E and the references are as follows:

Milner, CE, Davis, ID and Hamill, J. (2006) Relationship between free moment and tibial stress fractures. (in press) *Journal of Biomechanics*.

Milner, CE, Davis, ID, Ferber, R, Pollard, CD & Hamill, J (2006). Biomechanical factors associated with tibial stress fractures in female runners. *Med Sci Sport and Ex.*38, 323-328

Davis, IS (2005). Gait Retraining in Runners. *Orthopedic Physical Therapy Practice*, 17(2)8-13.

In addition two articles are currently in review:

Ferber, R, Noehren, B, Hamill, J, and Davis, I. (2006) Retrospective biomechanical investigation of iliotibial band syndrome in competitive female runners (in review), *Clin Biom*.

Milner, CE, Hamill, J and Davis, IS (2006) Does loading during early stance contribute to tibial stress fractures? (in review) *Journal of Bone and Joint Surgery*.

Additionally, six abstracts have been submitted and accepted for presentation since the last report. Four abstracts were presented at the American College of Sports Medicine National Meeting in Denver, Colorado in May 2006 and two will be presented at the American Society of Biomechanics in Blacksburg, Virginia in September 2006. These abstracts are included in Appendix 1 and the references are provided below.

Noehren, B, Davis, I and Hamill, J. Prospective study of the biomechanical factors associated with Iliotibial Band Syndrome To be presented at the American Society of Biomechanics Mtg, Blacksburg, Va, September, 2006

Crowell, HP and Davis, IS. Reducing lower extremity loads through gait retraining using real-time feedback methods. To be presented at the American Society of Biomechanics Mtg, Blacksburg, Va, September, 2006

Noehren, B, Ferber, R and Davis, I. Secondary plane biomechanics of Iliotibial Band Syndrome in competitive female runners. Presented at the American College of Sports Medicine Mtg, Denver, CO, May, 2006

Crowell, HP and Davis, IS. Between day reliability of accelerometry. Presented at the American College of Sports Medicine Mtg, Denver, CO, May, 2006

Zifchock, RA, Hamill, J and Davis, IS. Hip, knee and ankle velocities may predict injury risk in female distance runners. Presented at the American College of Sports Medicine Mtg, Denver, CO, May, 2006

Milner, CE, Hamill, J and Davis, IS. Are initial contact conditions related to tibial stress fractures

in distance runners. Presented at the American College of Sports Medicine Mtg, Denver, CO, May, 2006

From the data collected during the first five years, sixteen abstracts were submitted and presented at selected international conferences. The references are provided below.

Hamill, J, Haddad, JM. Milner, CE and Davis, IS. Intralimb Coordination in Female Runners with Tibial Stress Fractures. Presented at the International Society of Biomechanics Mtg, Cleveland, OH, August, 2005

Milner, CE, Davis, IS and Hamill, J. Does Free Moment Predict the Incidence of Tibial Stress Fractures? Presented at the International Society of Biomechanics Mtg, Cleveland, OH, August, 2005.

Seay, J, Haddad, JM. Milner, CE, Davis, IS and Hamill, J. Dynamic Symmetry in Female Runners with a History of Tibial Stress Fractures. Presented at the International Society of Biomechanics Mtg, Cleveland, OH, August, 2005.

Zifchock, RA, Davis, IS and Hamill, J. Kinetic Asymmetry in Left and Right Dominant Female Runners: Implications for Injury. Presented at the International Society of Biomechanics Mtg, Cleveland, OH, August, 2005.

Crowell, HP, Milner, CE, Hamill, J and Davis, IS. Short-term Retention of Gait Changes after Realtime Feedback to Reduce Shock. Presented at the American College of Sports Medicine Mtg, Nashville, TN, May, 2005.

Zifchock, RA and Davis, IS. Kinetic Asymmetry in Female Runners with and without Retrospective Tibial Stress Fractures. Presented at the American College of Sports Medicine Mtg, Nashville, TN, May, 2005.

Milner, CE, Davis, IS and Hamill, J. Is Dynamic Hip and Knee Malalignment associated with Tibial Stress Fractures in Female Distance Runners? Presented at the American College of Sports Medicine Mtg, Nashville, TN, May, 2005.

Milner, CE, Davis, IS And Hamill, J. Does Sustaining a Lower Extremity Stress Fracture alter Lower Extremity Mechanics in Runners? Presented at the American American Society of Biomechanics Mtg, Portland, OR, September 2004.

Davis, I, Milner, C and Hamill, J. Does Increased Loading during Running Lead to Tibial Stress Fractures: A Prospective Study. Presented at the American College of Sportsmedicine Meeting, Indianapolis, IA, June, 2004.

Milner, C, Davis, I and Hamill, J. Is Free Moment Related to Tibial Stress Fractures in Runners? Presented at the American College of Sportsmedicine Meeting, Indianapolis, IA, June, 2004.

McClay Davis, I, Dierks, TA, and Ferber, R. Lower extremity mechanics in patients with patellofemoral joint pain: A prospective study. Presented at the American Society of Biomechanics

Meeting, Toledo, OH, September, 2003.

McClay Davis, I, Ferber, R, Hamill, J and Pollard, CD. Rearfoot mechanics in competitive runners who had experienced plantar fasciitis. Presented at the International Society of Biomechanics Mtg in Dunedin, New Zealand in July, 2003

Ferber, R, McClay Davis, I, Hamill, J and Pollard, CD. Prospective biomechanical investigation of Iliotibial band syndrome in competitive female runners. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003

Pollard CD, McClay IS, Hamill J. Multiple Lower Extremity Stress Fractures in a Female Division I Cross-Country Runner: A Case Study. Presented at the Combined Sections Meeting of the APTA, Boston, MA, February 2002.

Ferber, R, McClay Davis, I, Hamill, J, Pollard, CD, and McKeown, KA. Kinetic Variables in Subjects with Previous Lower Extremity Stress Fractures. Presented at the American College of Sports Medicine Meeting in St. Louis, MO, June, 2002.

Pollard, CD, McKeown, KA, Ferber, R, McClay Davis, I and Hamill, J. Selected Structural Characteristics of Female Runners with and without Lower Extremity Stress Fractures. Presented at the American College of Sports Medicine Meeting in St. Louis, MO, June, 2002.

8) Presentations made

In addition to the conference presentations associated with the abstracts detailed above, the following invited presentations and symposias were made this year.

Davis, I. "Can We Alter Running Mechanics to Reduce Injury Risk in Runners? Symposium presented at the World Congress of Biomechanics Meeting, Munich, Germany, August, 2006

Hamill, J and Davis, I. "Can We Learn More from Prospective Rather than Retrospective Studies?" Symposium presented at the World Congress of Biomechanics Meeting, Munich, Germany, August, 2006

Davis, IS "Assessment and Reduction of Loading in Runners with Stress Fractures" Symposium presented at the American College of Sports edicine Meeting, Denver, CO, June, 2006

Davis, IS "The Development of Stress Fractures: The Tipping Point" Presented at Virginia Tech University, Blacksburg, VA, January, 2006

Davis, IS "The Dreaded Stress Fracture: Relationship to Mechanics". Presented at the Prescription Foot Orthotic Labs Association Meeting, Vancouver, Canada, November 2005

Davis, IS "The Dreaded Stress Fracture: Relationship to Mechanics". Keynote presented at the MidAtlantic ACSM Meeting, Harrisburg, PA, October, 2005.

Davis, IS "Running Right: Relationships between Mechanics and Injury" Keynote presented at the Sports Medicine Australia Meeting, Melbourne, Australia, October, 2005

In addition, the following presentations were made during the initial five years of the study.

Milner, C.E., Davis, I.S. & Hamill, J. "Is Dynamic Hip and Knee Malalignment Associated with Tibial Stress Fracture in Female Distance Runners?" Presented at the Center for Biomedical Engineering Research Symposium at the University of Delaware, USA, May 2005.

Davis, IS. "Is there a Right Way to Run: Relationships between Mechanics and Injury" Keynote presentation at the UK Sports Medicine Meeting, Nottingham, England, April 2005

Davis, IS "Is there a Right Way to Run: Relationships between Mechanics and Injury" Keynote presentation at the Running Medicine Meeting, Charlottesville, VA, March, 2005

Davis, IS. "Stress Fractures: Study of Relationship between Mechanics and Injury" Presentation given at the Australian Institute for Sport, Canberra, Australia, February 2005.

Davis, IS "The Use of Real-Time Feedback for Gait Retraining in Runners" Symposium presented at the Canadian Society of Biomechanics Meeting, August 2004

Dierks, T.A. & Davis, I. "Lower Extremity Joint Coupling and Patellofemoral Joint Pain during

Running” Presented at the Center for Biomedical Engineering Research Symposium at the University of Delaware, USA, May 2004.

Milner, C.E., Davis, I.S. & Hamill, J. ”Does Sustaining a Lower Extremity Stress Fracture Alter Lower Extremity Mechanics in Runners? Presented at the Center for Biomedical Engineering Research Symposium at the University of Delaware, USA, May 2004.

Davis, IS. “Is there a right way to run? Relationships between mechanics and injury” Presented at the Graduate Research Symposium, Penn State University, January, 2004,

Davis, IS “Is there a right way to run? Relationships between mechanics and injury” Presented at the National Congress of Sports Medicine in Stavanger, Norway, November, 2003.

Davis, IS. “Gait Retraining in Runners: An Application of the VICON Real-Time System” Presented at the Vicon Users' Group Meeting at the Gait and Clinical Movement Analysis Annual Meeting 2003, Wilmington, USA, May 2003.

9) Summary of information from the database

A summary of all the retrospective and prospective injury information we have collected is presented in tables 12 and 13. It is interesting to note the lower leg remains the most common site of retrospective injuries. Typically, the knee is the most common site of running injuries, with patellofemoral pain being the most common single injury at the knee. We feel this is because we initially advertised this study as a tibial stress fracture study and not as a running injury study. We have since changed this advertising strategy, and find that the difference is not as marked as in previous years.

In the prospective data, the injury pattern is more typical, with the knee being the most common site of injury and patellofemoral pain the second most common knee injury. Furthermore, the incidence of tibial stress fractures and tibial stress reaction is much reduced in the prospective database.

Table 12: Summary of retrospective injury information collected from the website database.

Injury Category	Incidence of Injury
Back TOTAL	40
Back sprain	3
Back strain	16
Disc pathology	2
Back other	19
Hip/ groin TOTAL	65
Gluteal strain/ tendinitis	3
Greater trochanteritis	13
Groin strain/ tendinitis	5
Pelvic stress fracture	5
Hip/ groin injury other	39
Thigh TOTAL	53
Femoral stress fracture	15
Hamstring strain	18
Quadriceps strain	11
Thigh other	9
Knee TOTAL	152
IT band friction syndrome	64
Lateral collateral strain	1
Medial collateral strain	3
Patellar tendinitis	14
Patellofemoral pain syndrome	42
Pes Anserinus tendinitis	1
Knee other	30
Lower leg TOTAL	197
Achilles tendonitis	21
Acute fibular fracture	4

Acute tibial fracture	2
Anterior compartment syndrome	7
Anterior tibialis strain	7
Fibular stress fracture	9
Gastroc/ soleus strain	6
Peroneal strain	4
Tibial stress fracture	46
Tibial stress reaction	65
Tibialis posterior strain	4
Posterior compartment syndrome	1
Lower leg other	23
Ankle	TOTAL
	78
Lateral ankle sprain	69
Medial ankle sprain	3
Ankle other	6
Foot	TOTAL
	123
Acute metatarsal fracture	6
Metatarsal stress fracture	21
Metatarsal stress syndrome	3
Neuroma	6
Painful 1 st MTP joint	2
Plantar fasciitis	45
Sesamoid fracture	3
Foot other	32
Other, region unspecified	17
TOTAL	725

Table 13: Summary of prospective injury information collected from the website database.

Injury Category	Incidence of Injury
Back	TOTAL
	31
Back sprain	10
Back strain	7
Back other	14
Hip/ groin	TOTAL
	60
Gluteal strain/ tendinitis	5
Greater trochanteritis	4
Groin strain/ tendinitis	11
Pelvic stress fracture	3
Hip other	37
Thigh	TOTAL
	59
Femoral stress fracture	8
Hamstring strain	29
Quadriceps strain	16
Thigh other	6
Knee	TOTAL
	133
IT band friction syndrome	47
Osteo-Arthritis	1
Osgood-Schlatter's syndrome	1
Lateral collateral strain	3
Patellar tendonitis	14
Patellofemoral pain syndrome	31
Pes Anserinus tendinitis	4
Knee other	32
Lower leg	TOTAL
	105
Achilles tendinitis	19
Anterior compartment syndrome	5
Anterior tibialis strain	6
Fibular stress fracture	3
Gastroc/ soleus strain	17
Peroneal strain	3
Tibial stress fracture	8
Tibial stress reaction	14
Tibialis posterior strain	8
Acute fibular fracture	1
Lower leg other	21
Ankle	TOTAL
	41
Lateral ankle sprain	26

Medial ankle sprain	8
Ankle other	7
Foot	TOTAL
Metatarsal stress syndrome	3
Metatarsal stress fracture	6
Painful 1 st MTP joint	3
Acute metatarsal fracture	2
Sesamoiditis	1
Neuroma	1
Plantar fasciitis	21
Retrocalcaneal bursitis	1
Sesamoid fracture	1
Foot other	31
Other, region unspecified	11
	TOTAL
	510

10) Degrees obtained that are supported by this award

Clare Milner was funded for a two-year Post-Doctoral Research Fellowship and has secured a faculty position in the Department of Exercise, Sport and Leisure Studies at the University of Tennessee in Knoxville, Tennessee, TN.

Tracy Dierks was funded on this award and graduated from the University of Delaware with a PhD from the Department of Physical Therapy in May 2005.

Andrea Fidler was funded on this award and graduated from the University of Massachusetts with a Master of Science from the Department of Exercise Science in September 2003.

Christine Pollard was funded on this award and will graduate from the University of Massachusetts with a Ph.D. from the Department of Exercise Science in September 2003.

Reed Ferber was funded for a two-year Post-doctoral Research Fellowship and graduated from the University of Delaware in July 2003.

Kelly Anne McKeown was funded on this award and graduated from the University of Massachusetts with a Master of Science from the Department of Exercise Science in April of 2002.

11) Employment or research opportunities applied for and/ or received based on experience/ training supported by the grant

Tracy Dierks has secured a faculty position in the Department of Physical Therapy at Indiana University Purdue University in Indianapolis, IN.

Reed Ferber has secured a post-doctoral research fellowship in the Human Performance Laboratory at the University of Calgary, Alberta, Canada.

Christine Pollard is currently working as a post-doctoral research fellow at the University of Southern California.

Kelly Anne McKeown is currently working as the biomechanist in the Shriners' Hospital Motion Analysis Laboratory in Springfield, MA.

CONCLUSIONS

This Annual Report focused on the fifth year status of this investigation. Seven specific work objectives were outlined and discussed with respect to adherence and methods used to meet all objectives in a timely manner. We have now recruited 430 subjects and will continue to recruit subjects in the high risk subgroup of young, high mileage runners during a one year no-cost extension. We hope this will provide us with more prospective tibial stress fractures in the coming 12 months.

To date, data on 430 subjects have been collected and analyses performed on: retrospective tibial stress fractures; prospective tibial stress fractures; six subjects who had experienced a tibial stress fracture during the study and returned for reassessment of their running mechanics following recovery and a return to training; and seven control subjects who did not sustain any lower extremity bony injuries. In addition, two new conference abstracts were presented on tibial stress fractures, highlighting the wide spectrum of injuries that this database is providing valuable information about. Three manuscripts have been accepted for publication, one relating lower extremity mechanics to the incidence of tibial stress fracture, the second relating free moment of vertical ground reaction force to the incidence of tibial stress fracture and the third relating the concept of gait retraining to reduce injury risk. An additional manuscripts, investigating initial loading characteristics in relation to tibial stress fracture is currently in review.

As with all prospective studies, the number of expected injuries can only be estimated. We expected to have approximately 20 tibial stress fractures at this point and only have 6. However, we have focused our recruitment in the past year to higher risk individuals, which we hope will yield more fractures. The inclusion of male runners in the study will also serve to increase the population of high risk individuals from which we can recruit. If this is not the case, we will likely pool our tibial stress reaction data (as proposed in the grant), along with the fibular stress fractures, which we believe likely have a similar mechanism of injury.

Overall, based on the retrospective data and preliminary prospective data, it appears that certain loading parameters such as loading rates, peak shock, and knee joint stiffness are related to the development of tibial stress fracture. Once we further validate these findings with additional data, we will be able to develop a simple, portable screening tool to predict those at increased risk for stress fractures. This would involve the use of a treadmill, accelerometer and laptop.

Once we are able to identify subjects at risk, we plan to develop interventions to reduce these risks. To this end, we have begun to develop protocols using realtime biofeedback to retrain gait patterns in order to reduce loading during running. This involves the same portable tool of a treadmill, accelerometer and laptop. We are in the process of testing these protocols through a number of case studies. Preliminary results are very promising and we believe this would be our next step in this line of research.

Our overarching goal is to reduce the risk of these serious and costly injuries to the military. We would propose to develop widespread screening throughout the military academies and ROTC programs. Once individuals are identified, they would be placed into a gait retraining program with realtime feedback to teach them to reduce their loads during running. Large-scale, prospective epidemiologic studies would then be conducted to determine whether reducing excessive loads during running resulted in lowering the incidence of stress fractures.

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Appendix A

Abstracts Presented at National and International Conferences.

1. Noehren, B, Davis, I and Hamill, J. Prospective study of the biomechanical factors associated with Iliotibial Band Syndrome. To be presented at the American Society of Biomechanics Mtg, Blacksburg, Va, September, 2006
2. Crowell, HP and Davis, IS. Reducing lower extremity loads through gait retraining using real-time feedback methods. To be presented at the American Society of Biomechanics Mtg, Blacksburg, Va, September, 2006
3. Noehren, B, Ferber, R and Davis, I. Secondary plane biomechanics of Iliotibial Band Syndrome in competitive female runners. Presented at the American College of Sports Medicine Mtg, Denver, CO, May, 2006
4. Crowell, HP and Davis, IS. Between day reliability of accelerometry. Presented at the American College of Sports Medicine Mtg, Denver, CO, May, 2006
5. Zifchock, RA, Hamill, J and Davis, IS. Hip, knee and ankle velocities may predict injury risk in female distance runners. Presented at the American College of Sports Medicine Mtg, Denver, CO, May, 2006
6. Milner, CE, Hamill, J and Davis, IS. Are initial contact conditions related to tibial stress fractures in distance runners. Presented at the American College of Sports Medicine Mtg, Denver, CO, May, 2006

Prospective Study of the Biomechanical Factors Associated with Iliotibial Band Syndrome

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INTRODUCTION

Iliotibial Band syndrome (ITBS) is the leading cause of lateral knee pain in runners. The Iliotibial band (ITB) originates proximally from the facial attachments of the gluteus medius, gluteus maximus and the tensor fascia late. Distally the ITB has attachments at the lateral femoral condyle, patella and at Gerdy's tubercle on the lateral tibia. The injury is thought to result from friction of the ITB sliding over the lateral femoral condyle. The mechanics that increase friction and exacerbate ITBS are not well understood, with few studies having been done to date.

It has been suggested that ITBS is related to a sagittal plane mechanism, whereby repetitive knee flexion causes friction between the ITB and the femoral condyle. However, Orchard et al. (1994) assessed knee flexion at initial contact, maximum knee flexion and time spent in knee flexion in runners with ITBS. They found no differences between the injured leg and uninjured leg in a group of runners.

It has also been suggested that a transverse plane mechanism may be at fault. Ferber et al. (2003) reported that runners with ITB exhibited a 7 deg increase in knee internal rotation compared with a control group. Increased knee internal rotation may be a result of increased ankle eversion due to the coupling between these joints. In fact Messier et al. (1994) found that the runners with ITBS exhibited greater peak eversion

as compared to controls. In addition, in a prospective study, Ferber et al. (2003) found that runners who went on to develop ITBS had greater peak eversion, greater peak eversion velocity and excursion.

A hip mechanism for developing ITBS has been proposed as well. Weakness of the hip abductors has been associated with ITBS (Fredrikson 2000). Weakness of the hip abductors has been shown to be related to increased hip adduction in runners with patellofemoral pain syndrome (Dierks 2005). However, there are no studies of the role of increased hip adduction in ITBS. It is possible that increased hip adduction combined with knee internal rotation, increases ITB tension. This could increase contact of the ITB with the lateral femoral condyle and lead to irritation with repeated exposure

The purpose of this study was to prospectively compare running mechanics in a group of female runners who went on to develop ITBS compared to healthy controls. It was hypothesized that runners who go on to develop ITBS would exhibit greater hip adduction, knee internal rotation and rearfoot eversion.

METHODS

This is an ongoing study where, to date, 17 female runners have developed ITBS prospectively. All injuries were confirmed by a medical professional such as a physician, physical therapist or an athletic

trainer. They were compared to a control group of 17 age and mileage matched uninjured runners. In both groups all runners were free from any previous or current hip and knee pathology.

Subjects ran over ground along a 25m runway at 3.7m/s wearing standard laboratory shoes. Five running trials were collected during the stance phase of running. Kinematic data was captured using a 6-camera motion capture system at 120Hz (Vicon, Oxford metrics, UK) and kinetics were captured using a force platform (Bertec OH, USA). Kinematic and kinetics were calculated using visual3D software (Visual 3D, C motion, MD, USA). Variables of interest were compared between groups using an independent, one tailed t-test.

RESULTS AND DISCUSSION

Comparison of the variables of interest between groups is presented in Table 1.

Table 1 Variables of Interest

	ITBS	CON	P
Peak EV (deg)	9.7	11.6	0.035
Peak Knee Int Rot	4.49	.021	0.001
Peak Hip Adduction	14.1	10.6	0.009

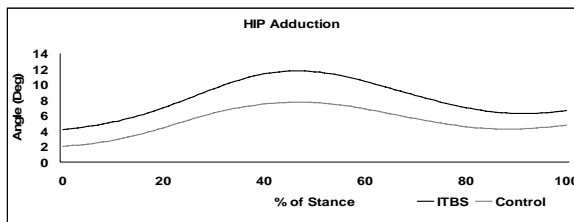


Figure 1 Hip adduction

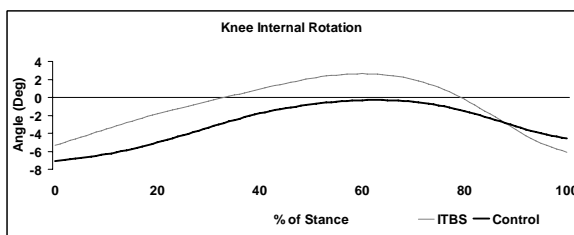


Figure 2 Knee internal rotation

As hypothesized (Fig 1), hip adduction was greater in the ITBS group. These findings suggest that hip weakness noted previously in runners with ITBS may result in excessive hip adduction. This would increase the tension on the ITB and, could lead to ITBS with repeated exposure.

The ITBS group also exhibited approximately a 4 deg increase in knee internal rotation (Fig 2). These findings are in support with Ferber et.al (2003). Increased knee internal rotation would elongate the ITB as its attachment at gerdy's tubercle is moved anteriorly. Unexpectedly, peak eversion was significantly lower in the ITBS group. This is contrast to Messier et al. (1995) and Ferber et al. (2003) who found greater peak eversion. However, it is possible that increased knee internal rotation was associated with increased talar navicular pronation, rather than subtalar pronation. Unfortunately, talar navicular motion is difficult to measure with standard motion analysis techniques.

SUMMARY/CONCLUSIONS

Results from this prospective study suggest that individuals who go onto to develop ITBS exhibit greater hip adduction and knee internal rotation. These results suggest that interventions should be directed at controlling these motions.

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REDUCING LOWER EXTREMITY LOADS THROUGH GAIT RETRAINING USING REAL-TIME FEEDBACK METHODS

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INTRODUCTION

Stress fractures are a common injury associated with the repetitive loads encountered during running and marching in basic combat training (BCT). A recent study of U.S. Army recruits found that 30% of the injuries sustained in BCT were stress fractures. Stress fractures are costly in terms of time and money. Rehabilitation time is 8 to 10 weeks (Hauret et al., 2001), and recruits who are discharged because they cannot complete their training cost the Army approximately \$10 M per year.

Prospective and retrospective studies have shown that subjects who sustain a tibial stress fracture have higher tibial shock than those who do not sustain a stress fracture (Milner et al., 2006; Davis et al., 2004). The rapid deceleration of the tibia at heel strike can lead to high strain rates in the bone which are suspected of being a cause of stress fractures (Fyhrie et al., 1998). Therefore, reducing these loads may result in reducing stress fracture risk.

Acute changes in lower extremity loads during running are possible in a single session of training with visual feedback (Crowell et al., 2005). However, long term retention of these changes has not been studied. Therefore, the purpose of this pilot study was to determine whether a longer period of training would result in reductions

in loading that would be evident one month after training.

METHODS

This is an ongoing study in which five subjects (3 females, 2 males) have participated to date. All subjects were between 20 and 34 years of age, ran at least 10 miles per week, and exhibited tibial shock greater than 8.9 g. Baseline three-dimensional kinematic and kinetic data were collected as subjects ran through the laboratory at 3.7 m/s ($\pm 5\%$).

For the retraining sessions, subjects ran on a treadmill at a self-selected pace. A uniaxial accelerometer was attached to the distal tibia on the side that had the highest shock, noted in the baseline data collection. Visual feedback of their tibial shock was provided on a monitor placed in front of them as they ran. Subjects were instructed to maintain their shock levels under 6 g as indicated by a line placed on the monitor.

The time for which subjects ran started at 10 minutes and increased to 30 minutes for the final sessions. Subjects were restricted from running outside the retraining sessions. Subjects received constant visual feedback for the first half of their sessions. The feedback was progressively removed over the remaining sessions such that subjects had three minutes of feedback in their final session. Immediately after the last

retraining session, kinematic and kinetic data were collected again. Then they ran on their own for four weeks and returned for a follow-up data collection. The first two subjects underwent retraining for 12 sessions over 4 weeks. However, because of the ease with which these subjects reduced their loading, the protocol was shortened to two weeks (8 sessions) for the remaining three subjects.

RESULTS

All subjects reduced their peak tibial shock from baseline at both post training and at 1 month follow-up (Figure 1).

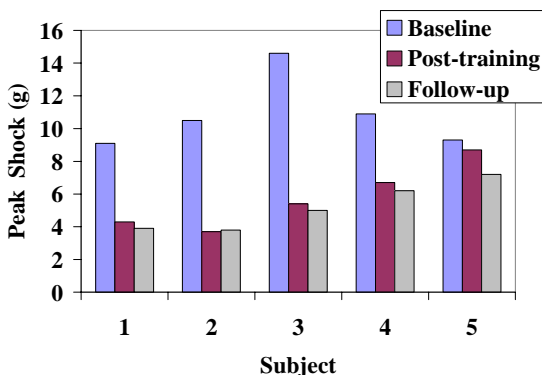


Figure 1: Peak shock at baseline, post-training and one month follow-up.

For the group, tibial shock decreased by approximately 50% (Table 1). Instantaneous vertical loading rate, vertical impact peak, and average vertical loading rate decreased by approximately 30%.

DISCUSSION

As expected, both the four week and two week protocol resulted in reductions in lower extremity loading that were maintained over the one month follow-up period. Feedback was only provided on tibial shock, which exhibited the greatest reduction from baseline. However, retraining also significantly reduced the

other three loading variables. The reductions in loading that the subjects achieved during this study likely reduce the strain and strain rates on their tibias, and thereby decrease their risk of stress fractures. Further analysis is underway to identify the kinematic strategies used by the subjects to reduce their lower extremity loading.

CONCLUSIONS

Based on these preliminary results, subjects are able to reduce their lower extremity loading by retraining with real-time visual feedback. These changes were maintained at one-month follow-up.

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Table 1. Lower extremity loading and changes for the group.

	Baseline	Post-training	1 month follow-up	Change (Baseline to Follow-up)
Tibial Shock (g)	10.8	5.8	5.2	-52 %
Inst. Load. Rate (BW/s)	84.7	58.6	54.8	-35 %
Impact Peak (BW)	1.6	1.3	1.2	-29 %
Avg. Load. Rate (BW/s)	69.8	47.5	47.6	-32 %

Secondary Plane Biomechanics of Iliotibial Band Syndrome in Competitive Female Runners

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Iliotibial band syndrome (ITBS) is the second leading cause of knee pain in runners and is the number one cause of lateral knee pain. The mechanisms by which runners develop ITBS are still poorly understood with few investigations looking at the contribution of the frontal and transverse planes of motion. It has been suggested increased motion in these planes would place greater tension on the ITB and result in ITBS over time.

PURPOSE: To retrospectively examine the biomechanical differences between a control group with no history of ITBS, and a group who have previously sustained ITBS in the past. It was hypothesized that runners who had previously sustained ITBS would exhibit greater peak rearfoot eversion (RFEV), knee internal rotation (KIR), hip adduction (HADD), hip internal rotation (HIR) angles. In addition greater knee frontal and transverse moments (KMOMY, KMOMZ) at initial impact peak of vertical ground reaction force were expected.

METHODS: 35 female runners, between the ages of 18-45 who have previously sustained ITBS, were recruited for the study. 35 age and mileage match female runners who had never had any hip or knee injuries, served as the controls. Subjects ran along a 25M runway at a speed of 3.7 m/s. Data from 5 trials were averaged for analysis using One tail independent t-test's for group comparisons (P<0.05).

RESULTS:

	RFEV	KIR	HADD	HIR	KMOMY	KMOMZ
Injured	52.44	1.7488	10.390	7.76	-.033	-0.023
Control	51.087	1.207	7.919	8.56	-.238	-0.006
P	0.430	0.027	0.049	.633	0.000	0.047

The ITBS group exhibited significantly greater KIR and HADD peak angles and greater KMOMY and KMOMZ compared to controls.

CONCLUSION: These data suggest that repetitive exposure to increased joint motion and loading over time would require greater restraint from the ITB and result in the cascade of events that cause ITBS. Prospective studies are necessary to more fully determine if these running biomechanics are predictive of future injury.

Supported by the Department of the Defense (DAMD17-00-1-0515)

Between Day Reliability of Accelerometry

Harrison P. Crowell, U.S. Army Research Laboratory and Irene S. Davis, FACSM, University of Delaware

PURPOSE An accurate and reliable measuring system is essential for collecting data to be used in gait analyses. However, there is little information available regarding the reliability of accelerometry during gait analyses. Therefore, the purpose of this study was to examine the between day reliability within and between testers for both treadmill and overground running.

METHOD Two experienced testers aligned and attached a small, lightweight, uniaxial accelerometer to the distal tibia of each subject (N=10: 2 females, 8 males). Testers palpated the anteromedial aspect of the distal tibia to find a flat spot without much soft tissue. Then they visually aligned the accelerometer with the long axis of the tibia. The accelerometer was initially held on the subject's skin with double sided tape. A piece of elastic tape was then put over the accelerometer to hold it more firmly. The alignment of the accelerometer was checked, and it was repositioned, if necessary. Finally, four strips of elastic tape were placed over the accelerometer and around the lower leg to secure the accelerometer. Each tester attached the accelerometer to the subjects for treadmill and overground trials on Day 1. The process was repeated the next day (Day 2). The dependent measure in this study was the peak positive acceleration measured by the accelerometer as subjects ran on a treadmill at 2.7 m/s and overground at 3.7 m/s through the laboratory. Intraclass correlation coefficients (ICC[2,k]) were calculated to determine the intra-tester and inter-tester reliability. **RESULTS** The intra-tester and inter-tester ICCs are shown in the table below.

Between Day Intraclass Correlation Coefficients (ICC[2,k])

	Intra-tester		Inter-tester	
	Tester 1	Tester 2	Day 1	Day 2
Treadmill	0.80	0.90	0.82	0.94
Overground	0.81	0.94	0.88	0.96

CONCLUSIONS The intra-tester ICCs show that each tester obtains reliable day-to-day measures (ICCs range from 0.80 to 0.94). The inter-tester ICCs show that the testers measures are consistent within each day for treadmill (ICC= 0.82 and 0.94) and overground (ICC= 0.88 and 0.96) trials. Therefore, based on these results, it appears that comparisons of peak positive acceleration between days and between testers can be made with confidence.

Hip, Knee, and Ankle Velocities May Predict Injury Risk in Female Distance Runners

Rebecca Avrin Zifchock, Irene Davis, and Joseph Hamill

Dynamic mal-alignment is often associated with injury risk in runners. Joint angle peaks and excursions are typically used to distinguish between injured and non-injured movement patterns. However, joint velocities may be useful for characterizing movement patterns during specific phases of gait, such as during the impact phase. **PURPOSE:** To compare joint velocities during impact to joint peaks and excursions for predicting injury risk. Elevated hip adduction (HADD), hip internal rotation (HINT), and rearfoot eversion (REV) peaks, excursions, and velocities were expected on the injured side. Elevated knee abduction (KABD) peaks and excursions, and decreased (less negative) knee adduction (KADD) velocities were also expected. **METHODS:** The injured and uninjured sides of 11 female runners with a history of retrospective and prospective, unilateral injury were compared. HADD, HINT, KABD, and REV data were collected using motion analysis. Synchronized force plate data were used to identify the stance phase and vertical impact peak for each trial; five for each leg. The peak joint angle, angle excursion from heel strike to peak, and average joint velocity from heel strike to vertical impact peak were extracted from each trial and averaged within each side. Paired t-tests were used to compare between sides, using each method ($\alpha = 0.05$). The percent difference between sides, as identified by each method, was also calculated. **RESULTS:** Although most of the variables showed the expected results, only KADD velocity was significantly different between limbs (94.3% decreased on the injured side). Of the peaks and excursions, only HADD excursion was more than 15% greater on the injured side. However, as for KADD, REV and HADD velocities were more than 20% and 60% greater on the injured side, respectively. **CONCLUSIONS:** Joint velocities during the impact phase of stance may distinguish between the injured and uninjured sides of runners better than peaks and excursions. These early stance joint velocities may provide insight into injury mechanisms which have not been previously explored.

		HADD	HINT	KABD (+), KADD (-)	REV
Peaks (degrees)	Inj: mean (sd)	10.2 (4.6)	6.7 (5.2)	2.4 (5.3)	10.8 (4.1)
	Uninj: mean (sd)	9.3 (4.0)	6.2 (4.8)	3.2 (2.8)	10.4 (3.3)
	T-test: p value	0.60	0.72	0.62	0.71
	% Difference	10.0	9.5	-25.6	3.4
Excursions (degrees)	Inj: mean (sd)	8.4 (2.1)	2.0 (2.3)	5.0 (2.2)	14.4 (5.3)
	Uninj: mean (sd)	7.1 (3.1)	2.2 (3.2)	5.2 (1.8)	13.8 (4.0)
	T-test: p value	0.22	0.79	0.77	0.71
	% Difference	17.4	-7.8	-4.3	4.2
Velocities (degrees/s)	Inj: mean (sd)	77.1 (60.0)	9.0 (64.8)	-3.3 (55.8)	118.8 (59.7)
	Uninj: mean (sd)	47.0 (54.5)	33.5 (53.6)	-58.1 (30.5)	98.4 (42.8)
	T-test: p value	0.15	0.21	0.01	0.20
	% Difference	64.0	-70.5	94.3	20.7

Are initial contact conditions related to tibial stress fracture in distance runners?

Clare E. Milner¹, Irene S. Davis FACSM², Joseph Hamill FACSM³

¹University of Tennessee, Knoxville, TN, ²University of Delaware, Newark, DE and ³University of Massachusetts, Amherst, MA

Runners with previous tibial stress fracture (TSF) have higher peak tibial shock (TSHK) and vertical loading rates than runners with no bony injuries. These events occur just after foot strike, before the body can respond to surface conditions. Therefore, different initial lower extremity compliance and leg angle may lead to differences in shock and loading rates which might be important in relation to TSF.

PURPOSE: To determine whether runners with previous TSF contact the ground with a stiffer lower extremity. That is, with a more flexed knee (KFLEX) and a more vertical leg (ALEG) at foot contact, plus a stiffer knee (KSTIF) and less flexion excursion (KEXC) from foot strike to impact peak than runners with no injury. A further purpose is to determine whether these variables are correlated with TSHK.

METHODS: Healthy runners who had sustained a TSF previously (RTSF; n = 20) and an age and mileage matched control group with no previous lower extremity bony injury (CTRL; n = 20) provided informed consent and participated. Gait data were collected at 120 Hz (960 Hz analog) as subjects ran at 3.7m/s on a 25m runway. Data from five trials were averaged for analysis. Independent t-tests and effect size (ES) were used to investigate the hypothesized differences between the groups. Pearson Product Moment correlations were used to determine whether initial contact variables were related to TSHK.

RESULTS: (Angles in degrees, stiffness is change in normalized joint moment (Nm/(mass in kg x height in m)) divided by change in joint angle)

	KSTIF*	KEXC	KFLEX	ALEG
RTSF	0.043	14.8	13.2	13.5
CTRL	0.031	16.4	12.0	14.3
<i>P</i>	0.042	0.297	0.571	0.419
ES	0.70	0.35	0.18	0.26

(*significant difference at $P \leq 0.05$ level)

Runners with previous TSF (and, therefore, higher TSHK) have higher KSTIF at initial contact than controls. Furthermore, KSTIF was moderately correlated with TSHK across the sample. Small effects with moderate correlations for KEXC and ALEG suggest that pose of the leg during initial contact is less important.

CONCLUSION: Knee stiffness is greater in runners with previous TSF, but the pose of the leg is not statistically different from controls. Prospective studies are needed to determine whether KSTIF is high prior to TSF.

Supported by Dept of Defense grant DAMD17-00-1-0515.

Appendix B
Advertisement Flyer



ATTENTION FEMALE RUNNERS



We are looking for Female Distance Runners who meet the criteria below to help better understand the mechanisms involved in Lower Extremity Running Injuries.



- ◆ Female runners are at a higher risk of sustaining a lower extremity running injury than males.
- ◆ Make a significant contribution to this area of research and gain a better understanding of your own lower extremity structure.

Inclusion Criteria:

- **Ages 18-30**
- **Run at least 20 miles per week**

Requirements: One two-hour data collection at the University of Delaware in Newark that includes a lower extremity evaluation by a licensed physical therapist and 3-D motion capture of your running gait. You will be compensated for your time.

Please contact Brian Noehren at 302-831-4646 or bnoehren@udel.edu

Running Injury Study Mike Pohl 831-4646 pohl@udel.edu	Running Injury Study Mike Pohl 831-4646 pohl @udel.edu	Running Injury Study Mike Pohl 831-4646 pohl @udel.edu	Running Injury Study Mike Pohl 831-4646 pohl @udel.edu	Running Injury Study Mike Pohl 831-4646 pohl @udel.edu	Running Injury Study Mike Pohl 831-4646 pohl @udel.edu	Running Injury Study Mike Pohl 831-4646 pohl @udel.edu	Running Injury Study Mike Pohl 831-4646 pohl @udel.edu	Running Injury Study Mike Pohl 831-4646 pohl @udel.edu
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Appendix D

Curriculum Vitae for Irene S. McClay

Irene S. Davis
Curriculum Vitae

PERSONAL

Address: 305 McKinly Lab, University of Delaware, Newark, DE 19716
Phone: (H): (302) 234-0532 (O): (302) 831-4263, (fax): (302) 831-4234
Email: mcclay@udel.edu www.udel.edu/pt/davis/index.htm
SSN: 047-40-3391

EDUCATION

PhD	1990	Pennsylvania State University	Biomechanics
MEd	1984	University of Virginia	Biomechanics
BS	1978	University of Florida	Physical Therapy
BS	1977	University of Mass.	Exercise Science

EMPLOYMENT

Director of Research, Drayer Physical Therapy Institute, (9/04 - present)

Development of research within the Joyner Sportsmedicine Institute aimed at advancing the science of sportsmedicine and improving prevention, diagnosis and treatment of orthopedic and sports-related injuries.

Director of Research, Joyner Sportsmedicine Institute, (6/97 - 8/04)

Development of research within the Joyner Sportsmedicine Institute aimed at advancing the science of sportsmedicine and improving prevention, diagnosis and treatment of sports-related injuries.

Associate Professor, Program in Physical Therapy, University of Delaware. (5/97 - present)

Assistant Professor, Program in Physical Therapy, University of Delaware. (9/89 - 5/97)

Instruction of graduate students in physical therapy. Research in biomechanics with specific interest in lower extremity mechanics and injury. Director, Running Injury Clinic.

Research Assistant, Pennsylvania State University, Center for Locomotion Studies. (8/85 - 6/89)

Responsible for the development and coordination of the Running Injury Clinic and Orthopedic Clinic. Research activities in locomotor biomechanics. Consultant to the Distance Runner's Camp at US Olympic Training Center.

Research and Teaching Assistant, University of Virginia, Rehabilitation Engineering Center. (8/82-8/85)

Research activities in wheelchair ergonomics. Instructor of graduate courses in biomechanics and human dissection. Co-coordinator of the Arts and Science of Sports Medicine Conference held annually at the University of Virginia (6/84, 6/85)

Physical Therapist, Blue Ridge Rehabilitation Associates, Charlottesville, VA (1/83 - 7/85)
Part time home health and private practice physical therapy.

Physical Therapist, Woodrow Wilson Rehabilitation Center, Fishersville, VA (2/79 - 6/82)
Patient treatment, supervision of physical therapy students, inservice training and Coordinator of the Amputee Clinic. Instructor in continuing education course in Management of the Spinal Cord Injured Patient.

Grants

Gait Retraining to Reduce Loading in Runners (in review). R01 submitted to the National Institutes of Health for **\$1.50 million** for 4 years.

Real-time Gait Retraining to Reduce Loading in Runners (in review). R01 submitted to the National Institutes of Health for **\$1.70 million** for 4 years.

The Use of an Instrumented Treadmill to Alter Locomotor Patterns. Army Research Office for \$230,000 for one year beginning 09/01/05

Gait Retraining in Runners through Realtime Feedback (in review). R01 submitted to the National Institutes of Health (NIAMS) for **\$453,000** for 3 yrs.

The Effect of Wedged Foot Orthoses on Lower Extremity Mechanics and Function in Patients with Knee Osteoarthritis. National Institutes of Health (COBRE Grant) **\$932,815** for 5 years beginning 02/2002.

A Comparison of Custom and Semicustom Foot Orthotic Devices on Lower Extremity Mechanics and Comfort in High and Low Arched Runners. The Pauline Marshall Research and Education Foundation, **\$22,000** for one year grant period beginning 2/2004 .

A Comparison of Custom and Semicustom Foot Orthotic Devices on Lower Extremity Mechanics and Comfort. The Pauline Marshall Research and Education Foundation, **\$15,000** for one year grant period beginning 9/2001 .

Biomechanical Factors Associated with the Etiology of Stress Fractures in Runners. The Department of the Army. **\$1.05 million** for 5 yr grant period beginning 9/2000.

2 Doctoral Scholarship. **\$20,000**. Joyner Sportsmedicine Institute, 1998, 1999, 2000, 2001; **\$36,000** for 2002. 2003

- Undergraduate Summer Scholarship. **\$4,000**. Joyner Sportsmedicine Institute, 1997 and 1998, 1999, 2000, 2001
- A Comparison of Four Methods to Obtain a Negative Impression of the Foot, **\$3,250**, Foot Management, Inc, 1998-1999
- The Effect of Different Orthotic Devices on Lower Extremity Mechanics of Rearfoot and Forefoot Strikers, **\$3,500**. Foot Management, Inc, 1999-2000.
- The Effect of the Protonics System on Patellar Alignment and Gait in Patients with Patellofemoral Joint Pain. **\$18,000**. Funded by Inverse Technology, 1998-1999
- Clinical Efficacy of the Protonics System in Patients with Patellofemoral Joint Pain. **\$3,000**. Funded by Inverse Technology, 1998-1999
- A Comparison of Strengthening vs. Orthotics on Pronation and Pronation Velocity. Funded by the Physical Therapy Foundation **\$60,000**, 1993-1995
- Lower Extremity Mechanics and Injury. Funded by the Whitaker Foundation **\$180,000**, 1993-1996.
- The Relationship between Subtalar Joint Axis Orientation, Joint Motion and Injuries in Runners. Funded by the Biomedical Research Support Grant. **\$2550**, 1992
- The Relationship between Subtalar Joint and Knee Joint Motion in Runners. Funded by the University of Delaware Research Foundation. **\$16,000**, 1990.
- A Comparison of Patellofemoral 3-D Kinematics in Runners with and without Patellofemoral Pain. Doctoral Dissertation. Foundation for Physical Therapy. **\$8500**, 1988.

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- Buchanan, K and McClay Davis, I. (2005). The Relationship between Forefoot Alignment and Rearfoot and Midfoot Compensation. (in press). *J. Orth. Sports PT*
- Pantano, KJ, White, SC, Gilchrist, IA, Leddy, J, and Davis, S (2005) Differences in Peak Knee Valgus Angles between Individuals with High and Low Q-angles During a Single Limb Squat. (in press) *Clin Biom*
- Denton, J, Willson, J, Ballantyne, B and **McClay Davis, I** (2005). Effect of the Protonics brace system in patients with patellofemoral pain syndrome. (in press) *Journal of Orthopedic and Sports Physical Therapy*

- Willson, J, Dougherty, C, Ireland, ML, and **McClay Davis, I** (2005). Core Stability: Relationship to lower extremity function and injury. (in press) *Journal of the American Academy of Orthopedic Surgeons*
- Ferber, R, and **McClay Davis, I** (2005). The effect of orthotics on lower extremity joint coupling. *Journal of Biomechanics* 38:477-483.
- Davis, I (2004). How do we accurately measure foot motion? Guest Editorial, *Journal of Orthopedic and Sports Physical Therapy* 34(9):503-504.
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- Pollard, C, McClay Davis, and I, Hamill, J. (2004) Influences of gender on hip and knee mechanics during an unanticipated cutting maneuver. *Clin Biomechanics* 19(10):1022-1031
- Deleo, A, Dierks, T, Ferber, R, and **McClay Davis, I** (2004) Joint coupling during running: An update. *Clinical Biomechanics* 19(10):983-991.
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- Williams, DS, McClay Davis, I and Baitch, S (2003).Effect of inverted orthoses on lower extremity mechanics. *Medicine and Science in Sport and Exercise*. 35(12):2060-2068.
- Ireland, ML, Ballantyne, B, Willson, J and **McClay Davis, I** (2003) The relationship between hip strength and patellofemoral joint pain. *Journal of Orthopedic and Sports Physical Therapy*.33(11):671-676

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- Willson, JD and **Davis, IS**. **Clinical quantification of frontal plane knee angle: Correlation of 2D and 3D motion analysis**. Presented at the American Society of Biomechanics Mtg, Portland, OR, September 2004.
- Dierks, TA, **Davis, IS**, and Hamill, J. Lower Extremity Joint Coupling in Runners who Develop Patellofemoral Pain Syndrome. Presented at the American American Society of Biomechanics Mtg, Portland, OR, September 2004.
- Milner, CE, **Davis, IS** And Hamill, J. Does Sustaining a Lower Extremity Stress Fracture alter Lower Extremity Mechanics in Runners? Presented at the American American Society of Biomechanics Mtg, Portland, OR, September 2004.
- Butler, RJ, **Davis, IS, Royer, T, Crenshaw, S and Mika, ES**. Differences in Frontal Plane Mechanics during Walking between Patients with Medial and Lateral Knee Presented at the American American Society of Biomechanics Mtg, Portland, OR, September 2004.
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- Dierks, TA & Davis, IS. "Lower Extremity Joint Coupling and Patellofemoral Joint Pain in Runners" Presented at the annual CBER Research Day, University of Del., May, 2004
- Butler, R, Davis, I, Royer, T and Crenshaw, S. "The effect of wedged orthotics on hip and ankle mechanics." Presented at the annual CBER Research Day, University of Del., May, 2004
- Willson, J. Ireland, ML, and Davis, I "The influence of lumbopelvic strength on lower extremity performance." Presented at the annual CBER Research Day, University of Del., May, 2004
- Cashen, C, Mika, ES, Butler, RJ, Royer, T, & Davis, IS. "The Effect of the Laterally Wedged Orthosis on Knee Kinematics and Kinetics in Patients with Medial Knee OA" Presented at the annual CBER Research Day, University of Del., May, 2004
- McClay Davis, I**, Dierks, TA, and Ferber, R. Lower extremity mechanics in patients with patellofemoral joint pain: A prospective study. Presented at the American Society of Biomechanics Meeting, Toledo, OH, September, 2003.
- Gupta, R and McClay Davis, I. Lower extremity mechanics behind successful orthotic intervention in patients with anterior knee pain. Presented at the American Society of Biomechanics Meeting, Toledo, OH, September, **2003**.
- Dierks, TA and McClay Davis, I. Discrete and continuous joint coupling during running. Presented at the American Society of Biomechanics Meeting, Toledo, OH, September, 2003.
- Butler, RJ, **McClay Davis, I**, Royer, T, Crenshaw, S and Mika, E. Toe-out effects frontal plane knee moments and angles in patients with knee osteoarthritis. Presented at the American Society of Biomechanics Meeting, Toledo, OH, September, 2003.

- Crenshaw, S, Royer, T, **McClay Davis, I**, Mika, E and Butler, R. The effect of laterally wedged insoles on standing alignment. Presented at the American Society of Biomechanics Meeting, Toledo, OH, September, **2003**.
- Richards, CJ, Card, K, Song, J, Hillstrom, H, Butler, R and **McClay Davis, I**. A novel arch height index measurement system (AHIMS): Intra- and inter-rater reliability. Presented at the American Society of Biomechanics Meeting, Toledo, OH, September, 2003.
- McClay Davis, I**, Ferber, R, Hamill, J and Pollard, CD. Rearfoot mechanics in competitive runners who had experienced plantar fasciitis. Presented at the International Society of Biomechanics Mtg in Dunedin, New Zealand in July, 2003
- Butler, RJ, **McClay Davis, I**, Royer, T, Crenshaw, S and Mika, ES. Acute effects of wedged orthoses on knee mechanics in patients with knee osteoarthritis. Presented at the International Society of Biomechanics mtg in Dunedin, New Zealand in July, 2003
- Ferber, R, **McClay Davis, I**, Hamill, J and Pollard, CD. Prospective biomechanical investigation of Iliotibial band syndrome in competitive female runners. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003
- Willson, JD, **McClay Davis, I** and Ireland, ML. Relationship between hip strength and tibiofemoral valgus angle during single leg squats. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003
- Dierks, TA, **McClay Davis, I**, and Ferber, R. Gender differences in discrete joint coupling variables during running. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003
- DeLeo, AT, Ferber, R, Mika, ES and **McClay Davis, I**. Comparison of rearfoot motion and comfort between custom and semi-custom orthotics based on arch height. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003
- Butler, RJ, Ferber, R and **McClay Davis, I**. Gender differences in lower extremity stiffness during running. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003
- Pollard, CD, Maclean, C, **McClay Davis, I** and Hamill, J. Knee joint kinematics during a single limb squat: Gender based differences in the collegiate soccer player. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003
- Ferber, R, **McClay Davis, I**, Hamill, J and Pollard, CD. Prospective biomechanical investigation of Iliotibial band syndrome in competitive female runners. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003

- McClay Davis, I**, Dierks, TA and Ferber, R. Gender differences in continuous joint coupling variables during running. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003
- Ferber, R, **McClay Davis, I**, Hamill, J. The effect of orthotics on lower extremity joint coupling. Variables associated with the incidence of lower extremity stress fractures. Presented at the World Congress of Biomechanics Mtg, Calgary, Canada, August, 2002.
- DeLeo, A, **McClay Davis, I** and Ferber, R. Custom and Semi-custom orthotic devices: A comparison of motion control and comfort. Presented at the World Congress of Biomechanics Mtg, Calgary, Canada, August, 2002.
- McClay Davis, I**, Ferber, R, Dierks, T, Butler, R, and Hamill, J. Variables associated with the incidence of lower extremity stress fractures. Presented at the World Congress of Biomechanics Mtg, Calgary, Canada, August, 2002.
- Pollard CD, **McClay IS**, Hamill J. Multiple Lower Extremity Stress Fractures in a Female Division I Cross-Country Runner: A Case Study. Presented at the Combined Sections Meeting of the APTA, Boston, MA, February 2002.
- McCrorry, JL, Quick NE, Ballantyne, BT, and **McClay Davis, I**. Effects of a Dynamic Knee Othosis on Subject Kinematics during the Lateral Step-Up Exercise. Presented at the American College of Sports Medicine Meeting in St. Louis, MO, June, 2002.
- Ferber, R, **McClay Davis, I**, Hamill, J,, Pollard, CD, and McKeown, KA. Kinetic Variables in Subjects with Previous Lower Extremity Stress Fractures. Presented at the American College of Sports Medicine Meeting in St. Louis, MO, June, 2002.
- Pollard, CD, McKeown, KA, Ferber, R, **McClay Davis, I** and Hamill, J. Selected Structural Characteristics of Female Runners with and without Lower Extremity Stress Fractures. Presented at the American College of Sports Medicine Meeting in St. Louis, MO, June, 2002.
- Leetun, DT, Ireland, ML, Ballantyne, BT and **McClay, IS**. Differences in Core Stability between Male and Female Collegiate Basketball Athletes as Measured by Trunk and Hip Performance. Presented at the ACL Research Retreat, Lexington, KY, April, 2001
- Ireland, ML, Ballantyne, BT, Little, K and **McClay, IS**. A Radiographic Analysis of the Relationship between the Size and Shape of the Intercondylar Notch and Anterior Cruciate Ligament Injury Presented at the ACL Research Retreat, Lexington, KY, April, 2001
- Shapiro, R, Yates, J, **McClay, I**, and Ireland, ML. Male-Female Biomechanical Differences in Selected Landing Maneuvers. Presented at the ACL Research Retreat, Lexington, KY, April, 2001

- Laughton, CA, **McClay, IS**, Hamill, J Effect of Orthotic Intervention and Strike Pattern on Tibial Shock in Runners. Presented at the International Society of Biomechanics, Zurich, Switzerland, July, 2001
- McClay, IS**, Hughes, MA, Laughton, CA, Gupta, R. Effect of Soft Orthotics on Tibial Shock and Rearfoot Motion. Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- Manal, KT & **McClay, IS** Errors in Estimating Tibial Translation during Natural Cadence Walking: Bone vs. Skin Mounted Tracking Markers. Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- Laughton, CA, **McClay, IS**, & J. Hamill. Effect of Foot Orthoses and Strike Pattern on Rearfoot Motion. Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- Ballantyne, BT, Leetun, D, Ireland, ML, & **McClay, IS**. Gender differences in core stability as measured by trunk and hip performance Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- McCrorry, JL, Quick, NE, Ballantyne, BT & **McClay, IS**. Effect of a Resistive Dynamic Knee Orthosis on Muscle Activations During the Lateral Step Up. Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- Laughton, CA and **McClay, IS**. Relationship between Loading Rates and Tibial Accelerometry in Forefoot Strike Runners. Presented at the Annual American Society of Biomechanics Mtg, Chicago, IL, July, 2000
- Williams, DS and **McClay, IS**. Lower Extremity Stiffness in Runners with High and Low Arches. Presented at the Annual American Society of Biomechanics Mtg, Chicago, IL, July, 2000.
- Manal, KT, **McClay, IS**, Richards, J and Stanhope, SJ. Effect of Marker Placement on Knee Joint Moments. Presented at the Canadian Society of Biomechanics Mtg, Montreal, July, 2000.
- Hamill, J, Heidersheidt, B, **McClay, IS**, Li, L. Influence of Strike Pattern on Lower Extremity Stiffness in Runners. Presented at the Canadian Society of Biomechanics Mtg, Montreal, July, 2000.
- Williams, DS and **McClay, IS**. Injury Patterns in Runners with Pes Cavus and Pes Planus. Presented at the ACSM National Mtg in Indianapolis, IN, **June**, 2000.
- Sahte, V, Ireland, ML, Ballantyne BT and **McClay, IS**. Acute Effect of the Protonics System on Patellofemoral Alignment. Presented at the ACSM National Mtg in Indianapolis, IN, June, 2000.

- Ott, S, Ireland, ML, Ballantyne, BT and **McClay, IS**. Gender Differences in Functional Outcomes following ACL Reconstruction. Presented at the ACSM National Mtg in Indianapolis, IN, **June**, 2000.
- Williams, DS, **McClay, IS** & Laughton, CA. A Comparison of between day Reliability of Different Types of Lower Extremity Kinematic Variables in Runners. Presented at the American Society of Biomechanics, October, **1999**, Pittsburgh, PA.
- McClay, IS**, Williams, DS & Laughton, CA. Can Gait be Retrained to Prevent Injury in Runners? Presented at the American Society of Biomechanics, October, 1999, Pittsburgh, PA.
- McClay, IS**, Williams, DS and Baitch, S. The Effect of the Inverted Orthotic on Lower Extremity Mechanics. Presented at the International Society of Biomechanics Mtg, August, 1999, Calgary, Canada
- McClay, IS**, & Williams, DS. Structure and Mechanics of Injured Twin Runners. Presented at the ACSM National Mtg in Seattle, WA, June, 1999.
- Wills, J & **McClay, IS**. Epidemiology of Extreme Sports. Presented at the ACSM National Mtg in Seattle, WA, June, 1999.
- Crook, S, Ballantyne, BT & **McClay, IS**. Reliability of a Functional Assessment Tool. Presented at the ACSM National Mtg in Seattle, WA, June, 1999.
- Laughton, CA, **McClay, IS** and Williams, DS. A Comparison of Methods of Obtaining a Negative Impression of the Foot. Presented at the National APTA Conference, Washington, DC, June, 1999.
- Williams, DS, **McClay, IS**. Reliability and Validity of Arch Characterizing Measurements. Presented at the Combined Sections Mtg of the APTA, Seattle, WA, February, 1999.
- McClay, IS**, Williams, DS, and Manal, KT. Lower Extremity Mechanics of Runners with a Converted Forefoot Strike Pattern. NACOB, Chicago, IL, 1998
- Manal, KT, **McClay, IS** et al. A Comparison of Surface Mounted Markers and Attachment Methods in estimating Tibial Rotations during Walking. Am. Soc. Biom. Mtg.,Clemson, SC, Oct, 1997
- McClay, IS** The Relationship between Lower Extremity Mechanics and Injury in Runners to be presented at the Whitaker Conference, Utah, August, **1996**.
- McClay, IS** & Manal, KT A Comparison of Rearfoot and Knee Kinematics during Running between Excessive Pronators and Normals. Presented at the Canadian Orthopedic Research Society Meeting, Quebec City, May, 1996.

- McClay, IS** & Manal, KT Lower Extremity Kinematic Comparisons between Forefoot and Rearfoot Strikers. Presented at the American Society of Biomechanics Meeting, Stanford, CA August, 1995.
- McClay, IS** & Manal, KT Lower Extremity Kinetic Comparisons between Forefoot and Rearfoot Strikers. Presented at the American Society of Biomechanics Meeting, Stanford, CA August, 1995.
- McClay, IS** & Manal, KT Coupling Parameters in Runners who Pronate and Normals. Presented at the American Society of Biomechanics Meeting, Columbus, Ohio, November, 1994.
- McClay, IS** & Manal, KT (1995). A Comparison of Two- and Three-dimensional Lower Extremity Kinematics during Running between Pronators and Normals. (Presented at the American Society of Biomechanics Meeting, Columbus, Ohio, November, 1994.
- McClay, IS**, Cavanagh, PR, Sommer, HJ, & Kalenak, A: "Three-Dimensional Kinematics of the Patellofemoral Joint during Running". Proceedings of the American Society of Biomechanics Meeting, October, 1991, Tempe, AZ.
- McClay, IS**, Cavanagh, PR, Sommer, HJ, & Kalenak, A: "The Effect of Orthotic Treatment on Tibiofemoral and Patellofemoral Joint Kinematics". *Physical Therapy*, 71(6):S46-7, 1991.
- McClay, IS**, Cavanagh, PR, Sommer, HJ, Woltring, HJ, & Kalenak, A: "Three-Dimensional Angular Kinematics of the Tibiofemoral Joint During Running". Proceedings of the International Symposium on 3-D Analysis of Human Movement, Montreal, July, 1991.
- Cavanagh, PR, Robinson, JR & **McClay, IS**: "Biomechanical Perspective of Stress Fractures in Professional Basketball Players". *Med Sci Sport and Exercise* 22:(2) S104, April, 1990.
- Woltring, HJ, **McClay, IS**, & Cavanagh, PR: "3-D Photogrammetric Camera Calibration without a Calibration Object." Abstract published in the Proceedings of the International Society of Biomechanics Meeting, Los Angeles, CA, June, 1989.
- McClay, IS**, Cavanagh, PR, & Kalenak, A: "Biomechanical Evaluation of the Injured Runner" Abstract published in the Proceedings of the East Coast Gait Conference, November, 1987.
- Brubaker, CE, **McClay, IS**, & McLaurin, CA: "Effect of Seat Position of Propulsion Efficiency." Proceedings of the 2nd International Conference on Rehabilitation Engineering, 1984, pp. 134-138.
- Brubaker, CE, **McClay, IS**, & McLaurin, CA: "The Effect of Mechanical Advantage on Lever Propulsion Efficiency". Proceedings of the 6th Annual Conference on Rehabilitation Technology, 1983, pp. 122-124.

SELECTED INVITED PRESENTATIONS

- Davis, IS. "Stress Fractures: Study of Relationship between Mechanics and Injury" Presentation given at the Australian Institute for Sport, Canberra, Australia, February 2005.
- Davis, IS. "Foot Structure, Mechanics and Injury Risk" Keynote Presentation at the 2nd International Foot and Ankle Symposium, Newark, DE, October 2004.
- Davis, IS. "The Effect of Laterally Wedged Foot Orthoses on Lower Extremity Mechanics of Patients with Medial Knee OA". Presented at the Prescription Foot Orthotic Laboratory of America (PFOLA) Mtg, Boston, MA, October, 2004.
- Davis, IS. "Is there a right way to run? Relationships between mechanics and injury" Presented at the and Science of Sports Medicine, Charlottesville, VA, June, 2004.
- Ireland, ML, Davis, IS, and Willson, J "The influence of lumbopelvic strength on lower extremity performance." Presented at the International ACL Study Group Mtg, Sardinia, Italy, June, 2004
- Davis, IS. "Relationships between structure and mechanics" Presented at the and Science of Sports Medicine, Charlottesville, VA, June, 2004.
- Davis, IS & Hamill, J. "The Biomechanical Etiology of Stress Fractures in Female Runners. Presented at the United States Army Research Institute of Environmental Medicine", May, 2004.
- Davis, IS. "Influence of Foot Biomechanics on Overuse Injuries of the Knee" Presented in the "Mechanisms of Knee Injuries: Implications for Prevention and Rehabilitation" Symposium. Combined Sections Mtg of the APTA, Nashville, TN, February, 2004
- Davis, IS. "Is there a right way to run? Relationships between mechanics and injury" Presented at the Graduate Research Symposium, Penn State University, January, 2004,
- Davis, IS "A Research Update on Orthotic Intervention" Presented at the Research Symposium at the Temple University College of Podiatric Medicine, December, 2003
- Davis, IS "Foot and ankle case studies in runners" Presented at the Research Symposium at the Temple University College of Podiatric Medicine, December, 2003
- Davis, IS "Is there a right way to run? Relationships between mechanics and injury" Presented at the National Congress of Sports Medicine in Stavanger, Norway, November, 2003.
- Davis, IS "The Role of Core Stability in Lower Extremity Injuries" Presented at the University of MA seminar series, Amherst, MA, November, 2003.

- Davis, IS "Comparison of Comfort and Rearfoot Control between a Semicustom and Custom Foot Orthoses" Presented at the Prescription Foot Orthotic Laboratory of America (PFOLA) Mtg, Las Vegas, NV, December 2003.
- Davis, IS "Biomechanical Considerations for Various Types of Foot Orthoses" Presented in the minisymposium titled "Clinical and Biomechanical Efficacy of Foot Orthoses" at the American College of Sports Medicine Mtg in San Francisco, CA, May, 2003.
- Davis, IS "Influence of Foot and Ankle Mechanics of Patellofemoral Joint Dysfunction: A Ground Up Biomechanical Perspective. Presented in the minisymposium titled "The Influence of Lower Quarter Mechanics on Patellofemoral Joint Dysfunction" at the American College of Sports Medicine Mtg in San Francisco, CA, May, 2003.
- Davis, IS "Case Studies in the Injured Runner" Presented at the Medical Aspects of Sports Medicine Mtg, University of Delaware, March, 2003.
- Davis, IS "Evidence for the Effect of Foot Orthoses on Lower Extremity Mechanics" Presented at Temple University College of Podiatric Medicine. February, 2003
- Davis, IS "The Relationship between Structure and Function in the Foot and Ankle". Presented at the Foot Management Inc. Mtg, Ocean City, MD, October 2002
- Davis, IS "Normal and Abnormal Gait" Presented at the Foot Management Inc. Mtg, Ocean City, MD, October 2002
- Davis, IS "The Effect of the Inverted Orthotic on Lower Extremity Mechanics in Patients with Patellofemoral Joint Pain. Presented at the Prescription Foot Orthotic Laboratory of America (PFOLA) Mtg, Montreal, Canada, October 2002.
- Davis, IS "Structural Deformities of the Foot: Assessment and Clinical Implications" Presented at the National Athletic Trainers Association Mtg, Dallas, TX, June,2002
- Davis, IS "Running Mechanics and Injury" Presented at the National Athletic Trainers Association Mtg, Dallas, TX, June,2002
- Davis, IS "The Role of Core Instability in Lower Extremity Injuries" Symposium: ACL Injuries and the Gender Bias. Presented at the American College of Sports Medicine Mtg in St. Louis, May, 2002.
- Davis, IS "Biomechanical Case Studies in Running Injuries" Symposium: Evidence for injury mechanisms in runners. Presented at the American College of Sports Medicine Mtg in St. Louis, May, 2002.
- " Davis, IS "The Application of Biomechanics to Sports Medicine: Focus on Running Injuries" **Keynote lecture** at the Midwest Student Biomechanics Symposium, Normal, IL, March, 2002.

- Davis, IS "Core Instability and Lower Extremity Mechanics: Implications for Injury." Presented at the Combined Sections Meeting of the APTA, Boston, MA, February, 2002.
- Davis, IS "An Update on the Mechanics behind the Success of Orthotic Intervention" Presented at Temple University School of Podiatric Medicine research seminar series, Philadelphia, PA, February 2002.
- Davis, IS "An Update on Orthotic Research: What do Orthotics do?" Presented at the Biokinesiology Graduate Research Seminar Series at the University of Southern California, Los Angeles, CA, November, 2001.
- Davis, IS "The Effect of the Inverted Orthotic on Lower Extremity Mechanics: An Update" Presented at the Prescription Foot Orthotic Laboratory Association Annual Meeting, Miami, FL, November, 2001
- Davis, IS "How Do Foot Orthotic Devices Influence Lower Extremity Mechanics. Presented at the Prescription Foot Orthotic Laboratory Association Annual Meeting, Miami, FL, November, 2001
- McClay, IS "Selected Case Studies in Running Injuries" Presented at the Combined Sections Meeting of the APTA, San Antonio, TX, Feb, 2001.
- McClay, IS "Developing Standards in Epidemiological Research" Presented at the National ACSM Mtg in Indianapolis, June, 2000
- McClay, IS "Lower Extremity Mechanics and Injury Patterns in High and Low Arch Runners". Keynote lecture presented at the Foot and Ankle Research Retreat, Annapolis, MD, May, 2000
- McClay, IS "Effect of the Inverted Orthotic on Rearfoot and Knee Mechanics" Presented at the 4th Annual John Weed Seminar, Palm Springs, CA, March, 2000 and the PFOA meeting in **Vancouver, BC**, November 2000
- McClay, IS "Influence of foot, knee and hip coupling on patellofemoral mechanics" Symposium at the Combined Sections Meeting of the APTA, New Orleans, LA, February, 2000 and at the National ACSM Mtg in Indianapolis, June, 2000, and the Arts and Science of Sports Medicine, Charlottesville, VA, June, 2000.
- McClay, IS "Visual Gait Analysis in Runners" Presented at the Arts and Science of Sports Medicine, Charlottesville, VA, June, 2000.
- McClay, IS "Injury Mechanisms in Runners" Keynote speaker at the Fifth IOC Congress on Sport Sciences, Sydney, Australia, November, 1999
- McClay, IS "Clinical Gait Analysis" Keynote speaker at the Fifth IOC Congress on Sport Sciences, Sydney, Australia, November, 1999.
- McClay, IS "Risk Factors in Anterior Cruciate Ligament Injuries" Clinical Colloquium presented at the National ACSM Mtg, in Seattle, WA, June, 1999

- McClay, IS "Problem Solving the Injured Runner" Clinical Colloquium presented at the National ACSM Mtg, in Seattle, WA, June, 1999
- McClay, IS "Coupling between the Foot and the Knee in Runners" Presented at Joyner Sportsmedicine Institute National Conference, Hilton Head, SC, October, 1999
- McClay, IS "Biomechanics of the Knee" Presented at Joyner Sportsmedicine Institute National Conference, Hilton Head, SC, October, 1999
- McClay, IS "Physical Therapist to Marathoner - A Classical Tale of Overuse." Presented at the Case Conference Seminar at the Annual Conference of the American Physical Therapy Association, Minneapolis, MN, June, 1998
- McClay, IS Eugene Michels Research Forum - "Instrumented versus Visual Gait Analysis in Clinical Assessments" Presented at the Combined Sections Mtg in Dallas, TX, Feb., 1997
- McClay, IS "Biomechanical Differences between Forefoot and Rearfoot Strikers" presented at the Joyner Sportsmedicine Institute National Conference, Hilton Head, SC, Nov. 1996.
- McClay, IS "Plantar Fasciitis:A Case Study" Presented at the Case Conference Seminar at the Annual Conference of the American Physical Therapy Association, Minneapolis, MN, June, 1996.
- McClay, IS "The Use of Motion Analysis in Physical Therapy". University of PA, Philadelphia, October, 1995.
- McClay, IS "The Patellofemoral Joint - Implications of the study of three-dimensional kinematics". Grand Rounds, Dept. of Orthopedic Surgery, Hershey Medical Center, January, 1995.
- McClay, IS "What is Clinical Research". Keynote Address at Research Symposium, Shenandoah University, April, 1994 .
- McClay, IS "Research in Foot and Ankle Biomechanics". Presented at the Combined Sections Meeting of the American Physical Therapy Association, New Orleans, LA, February, 1994
- McClay, IS "Biomechanical Assessment of Gait" Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1993
- McClay, IS "Closed Kinetic Chain Activities for the Foot and Ankle" Presented at the Foot and Ankle Seminar for HealthSouth in Orlando, FL, February, 1993, Phoenix, AZ, March, 1993, St. Louis, MO, April, 1993 and for Foot Mgt, Inc in Ocean City, MD in October, 1994 and April, 1996.
- McClay, IS "Normal Structure and Gait". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1992, and at the Symposium on the Biomechanics of the Lower Extremity, NATA, Denver, CO, February, 1992.

- McClay, IS "Abnormal Structure and Gait". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1992, and at the Symposium on the Biomechanics of the Lower Extremity, NATA, Denver, CO, February, 1992 and for Foot Mgt, Inc in Ocean City, MD in October, 1994 and April, 1996.
- McClay, IS "The Biomechanical Evaluation of the Injured Runner". Presented at the Medical Symposium of the Penn Relays, April, 1992, The Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1998 and the East Coast Gait Conference, Bethesda, Md, November, 1997
- McClay, IS "Biomechanics of the Foot and Ankle". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1991
- McClay, IS "Relationship between Mechanics and Running Injuries". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1991.
- McClay, IS "Anatomy and Biomechanics of the Patellofemoral Joint". Presented at the Sports Physical Therapy Meeting, Orlando, Fla. December, 1990
- McClay, IS "Relationship between Structure and Function in Patellofemoral Disorders". Presented at the Sports Physical Therapy Meeting, Orlando, Fla. December, 1990
- McClay, IS "Normal and Abnormal Running Mechanics". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va. June, 1990
- McClay, IS "Biomechanical Perspective of Stress Fractures in Professional Basketball Players". Presented at the Annual Meeting of the NBA Physicians, West Palm Beach, Fl, November, 1988.
- McClay, IS "The Biomechanics of Patellofemoral Disorders". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1988.
- McClay, IS "Biomechanical Profile of Elite Woman Distance Runners". Presented at the Dogwood Festival Pre-race Conference, Atlanta, GA, July, 1988.

CONTINUING EDUCATION

- Biomechanics of the Foot and Ankle. 2 day course sponsored by Drayer Physical Therapy Institute, Hummelstown, PA, February, 2004
- Biomechanics of the Foot and Ankle. 2 day course sponsored by NovaCare Physical Therapy, Chicago, IL, January, 2004
- Biomechanics of the Foot and Ankle. 2 day course sponsored by NovaCare Physical Therapy, Raleigh, NC, September, 2003

Biomechanics of the Foot and Ankle. 2 day course sponsored by NovaCare Physical Therapy, Alexandria, VA November, 2003

Biomechanic and Orthotic Treatment of the Foot and Ankle - 2 day course sponsored by Joyner Sportsmedicine Institute, Harrisburg, PA, March, 2001

Foot and Ankle Biomechanics and Orthotic Therapy. 2 day course sponsored by NovaCare Physical Therapy, Philadelphia March, 2000

Course on Orthotics. 2 day course presented to Foot Management, Inc, Ocean City, MD October, 2002

The Lower Kinetic Chain. 2 day course sponsored by Foot Management, Inc, Ocean City, MD October, 1998

HONORS

Fellow, American College of Sports Medicine	2001
Summa Cum Laude Graduate, The Penn State University	1990
Physical Therapy Foundation Scholar	1988
Recipient of Zipser Scholarship, The Penn State University	1988
Outstanding Masters Student Award, University of Virginia	1984
Nominee for Mary McMillan Scholarship Award, APTA	1978
Magna Cum Laude Graduate, University of Florida	1978
Magna Cum Laude Graduate, University of Massachusetts	1977

PROFESSIONAL ACTIVITIES

Societies

- American Society of Biomechanics
 - Abstract reviewer, Annual ASB Mtg, Chicago, IL, July 2000
 - Membership Committee (1997-2001)
 - Scientific Committee for the Third International Symposium on 3-D Analysis of Human Movement, Stockholm, Sweden, 1994
- American College of Sports Medicine, Fellow
- American Physical Therapy Association (APTA)
 - Orthopedic and Research Sections Member
 - Chairperson of Research Committee of the Foot and Ankle Special Interest Group (1997-present)
- International Society of Biomechanics

Advisory

Medical Consultant for Runners World (1995-present)

Ed. Board

Clinical Biomechanics (1999-present)

Journal of Orthopedic and Sports Physical Therapy (1996-1997)
Journal of Applied Biomechanics (1997-1999)

Reviewer Journal of Biomechanics
Medicine and Science in Sports and Exercise
Foot and Ankle, International
Journal of the American Podiatric Medical Association
Journal of Applied Biomechanics

NIH panels Invited Participant to the "Working Conference on Gait Analysis in Rehabilitation
Medicine" National Institutes for Health, September, 1996
NIH study section on Musculoskeletal Modeling, Chaired by Peter Cavanagh,
November, 2003

Other Organizing Chair for Research Retreat - Measurement of Foot Motion: Forward and
Inverse Dynamic Models, University of Southern California, Los Angeles, CA,
April, 2004
Organizing Chair for Research Retreat - ACL Injuries: The Gender Bias. Lexington, KY,
April 2001, 2003, 2006
Organizing Chair for Research Retreat - Static and Dynamic Classification of the Foot.
Annapolis, MD, May, 2000.
Member, Organizing Committee, Joyner Sportsmedicine Institute National Sportsmedicine
Conference, Hilton Head, SC (1996-1999)
Doctoral Research Advisory Committee (grant reviews), American Physical Therapy
Association (1995-1997)

Licensure Licensed Physical Therapist, State of Delaware

Appendix 5

Curriculum Vitae for Joseph Hamill

Last updated: 6/7/2005

CURRICULUM VITAE

Joseph Hamill

Professor and Chair, Department of Exercise Science
Associate Dean, School of Public Health and Health Sciences
University of Massachusetts Amherst
and
Professor, Neuroscience and Behavior Program
University of Massachusetts Amherst

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Department of Exercise Science
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(413) 545-2906 Fax
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PERSONAL DATA: Date of Birth: 3/3/46
Height: 5' 9"
Weight: 180 lbs
Citizenship: U.S.

EDUCATION

1967	Teaching Certificate	Lakeshore Teacher's College, Toronto, Canada
1972	B.A.	York University, Toronto, Canada
1977	B.S. (magna cum laude)	Concordia University, Montreal, Canada
1978	M.S.	University of Oregon, Eugene, Oregon
1981	Ph.D.	University of Oregon, Eugene, Oregon

Undergraduate Areas of Study: Political Science
General Science

Graduate Area of Study: Biomechanics

RESEARCH INTERESTS

Mechanics of lower extremity function
Mechanical Analysis of normal and pathological gait.
Modeling the lower extremity in gait.
Optimality criteria in human locomotion
Dynamical Systems

EMPLOYMENT EXPERIENCE

1981-1982 Post-doctoral Fellow
 Biomechanics Laboratory, University of Oregon

1982-1985 Assistant Professor (Biomechanics)
 Department of Physical Education, Southern Illinois University

1985-1986 Assistant Professor (Biomechanics) and Graduate Program Director
 Department of Physical Education, Southern Illinois University

1986-1988 Assistant Professor (Biomechanics)
 Department of Exercise Science, University of Massachusetts

1989-1995 Associate Professor (Biomechanics) and Graduate Program Director
 Department of Exercise Science, University of Massachusetts

1990-1995 Adjunct Professor
 Department of Medicine, University of Massachusetts Medical Center

1995-1996 Associate Professor (Biomechanics) and Department Chair
 Department of Exercise Science, University of Massachusetts

1996- Professor (Biomechanics) and Department Chair
 Department of Exercise Science, University of Massachusetts

2003- Professor and Associate Dean
 School of Public Health and Health Sciences, University of Massachusetts

RESPONSIBILITIES OF PRESENT POSITION

Associate Dean for Undergraduate Programs, School of Public Health and Health Sciences
Department Chair, Exercise Science
Director of the Biomechanics Laboratory
Teach graduate and undergraduate courses in Biomechanics
Advise undergraduate and graduate students

Chair graduate theses and dissertations in the Department
Conduct research in the area of Biomechanics
Secure external funding for the Biomechanics Laboratory

TEACHING RESPONSIBILITIES

Undergraduate

Ex Sc 300 Writing Seminar for Exercise Science
Ex Sc 305 Kinesiology
Ex Sc 304 Human Anatomy
Ex Sc 311 Anatomy of Human Motion
Ex Sc 474 Measurement and Evaluation Theory

Graduate

Ex Sc 531 Mechanical Analysis of Human Motion
Ex Sc 611 Introduction to Research
Ex Sc 732 Advanced Biomechanics
Ex Sc 892 Doctoral Seminar
Ex Sc 895 Clinical Biomechanics Seminar

UNIVERSITY SERVICE

Department Committees

Master's Thesis Review Committee, 1982-1983
Comprehensive Examination Review Committee, 1983-1984
Chair, Graduate Faculty, 1982-1986
Chair, Search Committee for Department Chairperson, 1986
Graduate Committee, 1986-
Telecommunications Committee, 1988-1990
Chair, Department Personnel Committee, 1994-1995
Chair, Motor Control Search Committee, 1994-1995
School Curriculum Committee, 2003-

College Committees

College Computer Advisory Committee, 1982-1986
School Personnel Committee, 1994-1995
School Executive Committee, 1995-
Member, School Development Officer Search Committee, 1997.

University Committees

Graduate Council, 1991
Recruitment and Retention Committee, 1991-92
Research Council, 1992-1995
Life Sciences Institute Advisory Council, 2003-
Undergraduate Deans Council, 2003-

PROFESSIONAL ORGANIZATIONS

American Alliance for Health, Physical Education, Recreation and Dance
Biomechanics Academy of the Research Consortium
International Society of Biomechanics
Canadian Society of Biomechanics
American Society of Biomechanics
American College of Sports Medicine
New England College of Sports Medicine
International Society of Biomechanics in Sport
ASTM
Association of Schools of Public Health

RESEARCH AFFILIATIONS

Scientific Advisory Board, Rockport Walking Institute, 1986-1992.
Scientific Advisory Board, LifeFitness, Inc., 1993-2004.
Scientific Advisory Board, USA Field Hockey, 1995-1998
USA Volleyball Sports Medicine and Performance Commission's Resource Advisory Committee, 1996-1999

ACADEMIC HONORS

Fellow, Research Consortium of the AAHPERD, 1984
Fellow, American College of Sports Medicine, 1986
Fellow, American Academy of Kinesiology and Physical Education, 1997
Award, Ruth Glassow Honor Award, Biomechanics Academy of NASPE, 2004

OFFICES IN PROFESSIONAL ORGANIZATIONS

1. Chair-elect, Kinesiology Academy, 1990-91.
2. Board Member, International Society of Biomechanics in Sports, 1992-94.
3. Chair, Biomechanics Interest Group of the American College of Sports Medicine, 1996-97.
4. Member-at-large, Executive Committee of the New England Chapter of the American College of Sports Medicine, 1995-1997.
5. Board Member, International Society of Biomechanics Technical Group on Footwear, 1998-2000.
6. Member, Credentials Committee, American College of Sports Medicine, 2000-2003.
7. Member-at-Large, Executive Board of Canadian Society of Biomechanics, 2000-2004
8. Member, Executive Board of the International Society of Biomechanics, 2003-

PROFESSIONAL SERVICE

Review Committees For Professional Meetings

1. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1989.
2. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1990.
3. Program Committee, combined meeting of the 9th International Symposium on Biomechanics in Sports and the Kinesiology Academy, June 29 - July 7, 1991.
4. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1991.
5. Review Panel Chair for Research Consortium, AAHPERD Convention, 1991-92.
6. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1992.
7. Review Panel Chair for Research Consortium, AAHPERD Convention, 1992-93.
8. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1993.
9. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1994.
10. Scientific Committee, International Society of Biomechanics in Sports Annual Meeting, Budapest, Hungary, June 1-6, 1994.
11. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1995.
12. Member, Scientific Review Committee, International Society of Biomechanics in Sports Annual Meeting, Madiera, Portugal, 1995-96.
13. Program Committee, New England American College of Sports Medicine Annual Meeting, Providence, RI, 1999.
14. Program Committee, New England American College of Sports Medicine Annual Meeting, Providence, RI, 2000.
15. Abstract Reviewer, XVIIIth Congress of the International Society of Biomechanics, ETH Zurich, Switzerland, July, 2001.
16. Abstract Reviewer, Vth Symposium of the Footwear Working Group Symposium of the International Society of Biomechanics, July, 2001.
17. Member, Research Consortium Research Writing Award Committee, 2001.
18. Member, Holyoke Community College Department of Health and Fitness Advisory Board, 2001-
19. Member, Scientific Review Committee, International Society of Biomechanics in Sports Annual Meeting, Caceres, Spain, 2002.
20. Member, Scientific Review Committee, International Society of Biomechanics in Sports Annual Meeting, Beijing, China, 2003.
21. Member, Scientific Review Committee, International Society of Biomechanics in Sports Annual Meeting, Ottawa, Canada, 2004.
22. Abstract Reviewer, American College of Sports Medicine Annual Meeting, 2004.
23. Abstract Reviewer, American College of Sports Medicine Annual Meeting, 2005.
23. Abstract Reviewer, VIIth Symposium of the Footwear Working Group Symposium of the International Society of Biomechanics, August, 2005.
24. Member, Organizing Committee, VIIth Symposium of the Footwear Working Group Symposium of the International Society of Biomechanics, August, 2005.
25. Abstract Reviewer, XXth Congress of the International Society of Biomechanics, Cleveland, OH, USA, August, 2005.
26. Member, Scientific Review Committee, International Society of Biomechanics in Sports Annual Meeting, Beijing, China, 2005.

External Reviewer for Theses and Dissertations

1. External Dissertation Reviewer, McMaster University, Hamilton, Ontario, Canada, June, 1995.
2. External Thesis Reviewer, Lakehead University, Thunder Bay, Ontario, Canada, June, 1995.
3. External Dissertation Reviewer, University of Guelph, Guelph, Ontario, Canada, January, 1997.
4. External Dissertation Reviewer, University of Connecticut, Storrs, Connecticut, December, 1998.
5. External Dissertation Reviewer, University of Delaware, Newark, Delaware, March, 2000.
6. External Thesis Reviewer, University of Delaware, Newark, Delaware, November, 2000.
7. External Dissertation Reviewer, University of Calgary, Calgary, Alberta, Canada, November, 2002.
8. External Dissertation Reviewer, Auckland University of Technology, Auckland, New Zealand, June, 2004.
9. External Dissertation Reviewer, University of Edinburgh, Edinburgh, Scotland, December, 2004.
10. External Dissertation Reviewer, University of Western Australia, Perth, Australia, March, 2005.
11. External Dissertation Reviewer, University of Delaware, Newark, Delaware, May, 2005.
12. External Dissertation Reviewer, Sheffield Hallam University, Sheffield, England, May, 2005.

External Grant Reviewer

1. External Reviewer for internal grants at University of Texas at Tyler, 1991.
2. Grant Reviewer, Natural Sciences and Engineering Council of Canada, 1993.
3. External Grant Reviewer, University Grants Committee, Hong Kong, February, 1998.
4. External Grant Reviewer, Natural Sciences and Engineering Council of Canada, May, 2000.
5. External Grant Reviewer, Canadian Institutes of Health Research, April, 2003.
6. External Grant Reviewer, USARIEM, Natick, MA, May, 2004.
7. External Grant Reviewer, Canadian Institutes of Health Research, April, 2004.
8. Grant Reviewer, Natural Sciences and Engineering Council of Canada, December, 2004.

Committee Member

1. Biomechanics Model Research Laboratory, Olympic Scientific Congress, University of Oregon, July, 1984.
2. Completed Research in Health, Physical Education, Recreation and Dance, 1986.
3. Research Consortium Program Review Committee, AAHPERD Annual Convention, April, 1987.
4. Kinesiology Academy, Nominating Board for Officers, 1987.
5. Completed Research in Health, Physical Education, Recreation and Dance, 1988.
6. Nominating Committee for Kinesiology Academy Chair, 1991.
7. Delegate to American Alliance Assembly, January 1, 1991 to December 31, 1991.
8. ASTM Committee F-8 on Sports Equipment and Facilities, June, 1992.

9. Conference Chair, International Society of Biomechanics in Sport Annual Meeting, University of Massachusetts Amherst, June 23-26, 1993.
10. Doctoral Program Evaluation Committee, American Academy of Kinesiology and Physical Education, 1997.
11. Program Review Committee for Biomechanics, Michigan State University, East Lansing, MI, January, 2000.
12. Continuing Committee for Doctoral Program Review, American Academy of Kinesiology and Physical Education, 2001-2002
13. Member, Research Consortium Research Writing Award Committee, 2001.
14. Member, AAHPERD Grant Proposal Committee, 2001.
15. Member, Holyoke Community College Department of Health and Fitness Advisory Board, 2001-
16. Coordinator, Grant Program of the Research Consortium, 2004-.

EDITORIAL BOARD OF PROFESSIONAL JOURNALS

Member, Editorial Review Board, *Pediatric Exercise Science*, 1988-
 Member, Editorial Review Board, *Medicine, Exercise, Nutrition, and Health*, 1991-1995
 Guest Editor, Special Issue of *Pediatric Exercise Science*, The Physically Challenged Child, May, 1992.
 Section Editor, Biomechanics, *Research Quarterly for Exercise and Sport*, 1993-96
 Member, Editorial Review Board, *Journal of Applied Biomechanics*, 1996-1999
 Member, Editorial Board, *Research Quarterly for Exercise and Sport*, 1998-1999
 Associate Editor, *Medicine and Science in Sports and Exercise*, 2000-2002
 Member, Editorial Review Board, *Sports Biomechanics*, 2000-
 Member, Editorial Review Board, *Journal of Sports Sciences*, 2001-
 Member, Editorial Review Board, *Exercise and Sports Science Review*, 2005-

AD HOC REVIEWER FOR PROFESSIONAL JOURNALS

Reviewer, *Medicine and Science in Sports and Exercise*, 1985-
 Reviewer, *International Journal of Sports Biomechanics*, 1986-
 Reviewer, *Research Quarterly for Exercise and Sport*, 1989-
 Reviewer, *Sports Medicine*, 1991-
 Reviewer, *Journal of Gerontology*, 1991-
 Reviewer, *Journal of Orthopedic and Sports Physical Therapy*, 1991-
 Reviewer, *Journal of Applied Biomechanics*, 1993-
 Reviewer, *Journal of Applied Physiology*, 1993-
 Reviewer, *Journal of Biomechanics*, 1993-
 Reviewer, *Clinical Journal of Sports Medicine*, 1996-
 Reviewer, *British Journal of Sports Medicine*, 1996-
 Reviewer, *Clinical Biomechanics*, 1999-
 Reviewer, *Exercise and Sports Science Review*, 2000-
 Reviewer, *European Journal of Applied Physiology*, 2000-
 Reviewer, *Journal of Rehabilitation Research and Development*, 2002-

PUBLICATIONS

Osternig, L. R., Sawhill, J. A., Bates, B. T., **Hamill, J.** A method for rapid collection and processing of isokinetic data. *Research Quarterly for Exercise and Sport* 53(3):252-257, 1982.

Knutzen, K. M., Bates, B. T., **Hamill, J.** Electrogoniometry of post surgical knee bracing in running. *American Journal of Physical Medicine* 62(4):172-181, 1983.

Osternig, L. R., **Hamill, J.**, Sawhill, J. A., Bates, B. T. Influence of torque and joint speed on power production. *American Journal of Physical Medicine* 62(4): 163-171, 1983.

Hamill, J., Bates, B. T., Sawhill, J. A., Knutzen, K. M. Variations in ground reaction force parameters at different running speeds. *Human Movement Sciences* 2:47-56, 1983.

Hamill, J., Bates, B. T., Knutzen, K. M. Ground reaction force symmetry during walking and running. *Research Quarterly for Exercise and Sport* 55(3):289-293, 1984.

Knutzen, K. M., Bates, B. T., **Hamill, J.** Knee brace influences on the tibial rotation and torque patterns of the surgical limb. *Journal of Orthopaedic and Sports Physical Therapy* 6(2):116-122, 1984.

Osternig, L. R., **Hamill, J.**, Corcos, D. M., Lander, J. E. Electromyographic patterns accompanying isokinetic exercise under varying speed and sequencing conditions. *American Journal of Physical Medicine* 63(6):289-297, 1984.

Knutzen, K. M., **Hamill, J.**, Bates, B. T. Ambulatory characteristics of the visually disabled. *Human Movement Sciences* 4:55-66, 1985.

Lander, J. E., Bates, B. T., Sawhill, J. A., **Hamill, J.** A comparison between free-weight and isokinetic bench pressing. *Medicine and Science in Sports and Exercise* 17(3): 344-353, 1985.

Smith, P. K., **Hamill, J.** The effect of punching glove type and skill level on momentum transfer. *Human Movement Studies* 12(3):153-161, 1986.

Hamill, J., Knutzen, K. M., Bates, B. T., Kirkpatrick, G. M. Evaluation of two ankle appliances using ground reaction force data. *Journal of Orthopaedic and Sports Physical Therapy* 7(5):244-249, 1986.

Osternig, L. R., **Hamill, J.**, Lander, J. E., Robertson, R. Coactivation of sprinter and distance runner agonist/antagonist muscles in isokinetic exercise. *Medicine and Science in Sports and Exercise* 18(4):431-435, 1986.

Hamill, J., Ricard, M. D., Golden, D. M. Angular momentum in multiple rotation non-twisting platform dives. *International Journal of Sport Biomechanics* 2(2): 78-87, 1986.

Knutzen, K. M., Bates, B. T., Schot, P., **Hamill, J.** Knee brace evaluation. *Medicine and Science in Sports and Exercise* 19(3):303-309, 1987.

Hamill, J., Murphy, M. V., Sussman, D. H. The effects of track turns on lower extremity function. *International Journal of Sport Biomechanics* 3(3):276-286, 1987.

Hamill, J., Morin, G., Clarkson, P. M., Andres, R. O. Exercise moderation of foot function during walking with a re-usable semirigid ankle orthosis. *Clinical Biomechanics* 3(3):153-158, 1988.

Hamill, J., Bates, B. T. A kinetic evaluation of the effects of in vivo loading on running shoes. *Journal of Orthopaedic and Sports Physical Therapy* 10(2):47-53, 1988.

Hamill, J., Freedson, P. S., Boda, W., Reichsman, F. Effects of shoe type and cardiorespiratory responses and rearfoot motion during treadmill running. *Medicine and Science in Sports and Exercise* 20(5):515-521, 1988.

Greer, N. L., **Hamill, J.**, Campbell, K. R. Ground reaction forces in children's gait. *Pediatric Exercise Science* 1(1):45-53, 1989.

Hamill, J., Knutzen, K. M., Bates, B. T., Kirkpatrick, G. M. Relationship of static and dynamic measures of the lower extremity. *Clinical Biomechanics* 4(4):217-225, 1989.

Greer, N. L., **Hamill, J.**, Campbell, K. R. Dynamics of children's gait. *Human Movement Sciences* 8:465-480, 1989.

Brown, D. B., Knowlton, R. G., **Hamill, J.**, Schneider, T. L., Hetzler, R. K. Physiological and biomechanical differences between wheelchair-dependent and able-bodied subjects during wheelchair ergometry. *European Journal of Applied Physiology* 60:179-182, 1990.

Holt, K. G., **Hamill, J.**, Andres, R. O. The force driven harmonic oscillator as a model for human locomotion. *Human Movement Science* 9:55-68, 1990.

Hamill, J., McNiven, S. L. Reliability of ground reaction force parameters during walking. *Human Movement Science* 9:117-131, 1990.

Robertson, R. N., Osternig, L. R., **Hamill, J.**, DeVita, P. EMG-torque relationships during isokinetic dynamometer exercise. *Sports Training, Medicine and Rehabilitation* 2:1-10, 1990.

Holt, K. G., **Hamill, J.**, Andres, R. O. Predicting the minimal energy cost of human walking. *Medicine and Science in Sports and Exercise* 23(4):491-498, 1991.

Hamill, J., Freedson, P. S., Clarkson, P. M., Braun, B. Muscle soreness during running: biomechanical and physiological implications. *International Journal of Sports Biomechanics* 7(2):125-137, 1991.

Devita, P., Hong, D. M., **Hamill, J.** Effects of asymmetric load carrying on the biomechanics of walking. *Journal of Biomechanics* 24(12):1119-1129, 1991.

Ebbeling, C. J., **Hamill, J.**, Freedson, P. S., Rowland, T. W. Efficiency in Children's Gait. *Pediatric Exercise Science*. 4(1):36-49, 1992.

Widrick, J., Freedson, P. S., **Hamill, J.** Effect of internal work on the calculation of optimal pedalling rates. *Medicine and Science in Sports and Exercise* 24(3): 376-382, 1992.

Hamill, J., Bates, B. T., Holt, K. G. Timing of lower extremity joint actions during treadmill running. *Medicine and Science in Sports and Exercise* 24(7):807-813 1992.

Foti, T., Ebbeling, C. J., **Hamill, J.**, Ward, A., Rippe, J. Stair climbing machines: Lower extremity kinematics and exercise intensity comparisons. *Medicine, Exercise, Nutrition, and Health* 2:162-169, 1993.

Ebbeling, C. J., **Hamill, J.**, Crussemeyer, J. A. Lower extremity mechanics and the energy cost of walking in high-heeled shoes. *Journal of Orthopaedic and Sports Physical Therapy* 19 (4):190-196, 1994.

Holt, K. G., Jeng, S. F., Ratcliffe, R., **Hamill, J.** Energetic cost and stability during human walking at the preferred stride frequency. *Journal of Motor Behavior* 27(2): 164-178, 1994.

Hamill, J., Derrick, T. R., Holt, K. G. Shock attenuation and stride frequency during running. *Human Movement Science* 14:45-60, 1995.

Whittlesey, S. N., **Hamill, J.** An alternative model of the lower extremity during locomotion. *Journal of Applied Biomechanics* 12(2):269-279, 1996.

Jensen, R. L., Freedson, P. S., **Hamill, J.** The prediction of power and efficiency during near-maximal rowing. *European Journal of Applied Physiology* 73:98-104, 1996.

Hamill, J., Caldwell, G. E., Derrick, T. R. Reconstructing digital signals using Shannon's Sampling Theorem. *Journal of Applied Biomechanics* 13:226-238, 1997.

Mahar, A. T., Derrick, T. R., **Hamill, J.**, Caldwell, G. E. Impact shock and attenuation during in-line skating. *Medicine and Science in Sports and Exercise* 29(8):1069-1075, 1997.

Derrick, T. R., **Hamill, J.**, Caldwell, G. E. Energy absorption in conditions of various stride frequencies. *Medicine and Science in Sports and Exercise* 30(1):128-135, 1998.

Hamill, J., van Emmerik, R. E. A., Heiderscheit, B. C., Li, L. A dynamical systems approach to the investigation of lower extremity running injuries. *Clinical Biomechanics* 14(5):297-308, 1999.

- Li, L., Hardin, E. C., Caldwell, G. E., Van Emmerik, R. E. A., **Hamill, J.** Coordination patterns of walking and running at similar speed and stride frequency. *Human Movement Science* 18:67-85, 1999.
- Heiderscheit, B. C., **Hamill, J.**, Van Emmerik, R. E. A. Influence on Q-angle on the variability of lower extremity segment coordination during running. *Medicine and Science in Sport and Exercise* 31(9):1313-1319, 1999.
- Derrick, T. R., Caldwell, G. E., **Hamill, J.** Modeling the stiffness characteristics of the human body while running at various stride frequencies. *Journal of Applied Biomechanics* 16:36-51, 2000.
- Heiderscheit, B. C., **Hamill, J.**, Caldwell, G. E. Influence on Q-angle on lower extremity kinematics during running. *Journal of Orthopedic and Sports Physical Therapy*, 30(5):271-278, 2000.
- McCaw, S. T., Heil, M. E., **Hamill, J.** The effect of comments about shoe construction on impact forces during walking. *Medicine and Science in Sport and Exercise* 32(7):1258-1264, 2000.
- Whittlesey, S. N., Van Emerik, R. E. A., **Hamill, J.** The swing phase of human walking is not a passive movement. *Motor Control*, 4(3):273-292 2000.
- Hamill, J.**, Haddad, J.M., McDermott, W.J. Issues in quantifying variability from a dynamical systems perspective. *Journal of Applied Biomechanics*, 16:409-420, 2000.
- Williams, D. S., McClay, I. S., **Hamill, J.**, Buchanan, T. S. Lower extremity kinematic and kinetic differences in runners. *Journal of Applied Biomechanics* 17:153-163, 2001.
- Williams, D. S., McClay, I. S., **Hamill, J.** Arch structure and injury patterns in runners. *Clinical Biomechanics* 16(4):341-347, 2001
- O'Connor, K. M., **Hamill, J.** Does running on a cambered road predispose a runner to injury? *Journal of Applied Biomechanics* 18(1):3-14, 2002.
- Heiderscheit, B. C., **Hamill, J.**, Van Emmerik, R. E. A. Locomotion variability and patellofemoral pain. *Journal of Applied Biomechanics* 18(2):110-121, 2002.
- Hardin, E. C., **Hamill, J.** The influence of midsole cushioning on mechanical and hematological responses during a prolonged downhill run. *Research Quarterly for Exercise and Sport* 73(2):125-133, 2002.
- Li, L., **Hamill, J.** Characteristics of the vertical ground reaction force component prior to gait transition. *Research Quarterly for Exercise and Sport* 73(3):229-237, 2002.
- Mercer, J. A., Vance, J., Hreljac, A., **Hamill, J.** Relationship between shock attenuation and stride length during running at different velocities. *European Journal of Applied Physiology* 87:403-408, 2002.

- Peters, B. T., Haddad, J. M., Heiderscheit, B. C., Van Emmerik, R. E. A., **Hamill, J.** Limitations in the use and interpretation of continuous relative phase. *Journal of Biomechanics* 36:271-274, 2003.
- Laughton, C. A., McClay, I. S., **Hamill, J.** Effect of strike pattern and orthotic intervention on tibial acceleration during running. *Journal of Applied Biomechanics* 19(2):153-168, 2003.
- McDermott, W. J., Van Emmerik, R. E. A., **Hamill, J.** Running training and adaptive strategies of locomotor/respiratory coordination. *Journal of Applied Physiology* 89:453-444, 2003.
- Laughton Stackhouse, C. A., McClay Davis, I. S., **Hamill, J.** Orthotic intervention in forefoot and rearfoot strike running patterns. *Clinical Biomechanics* 19:64-70, 2004.
- O'Connor, K. M., **Hamill, J.** The role of extrinsic foot muscles during running. *Clinical Biomechanics* 19:71-77, 2004.
- Williams, D.S., McClay-Davis, I., Scholz, J.P., **Hamill, J.**, Buchanan, T.S. High arched runners exhibit increased leg stiffness compared to low arched runners. *Gait and Posture* 19(3):263-269, 2004.
- Hardin, E. C., Van Den Bogert, A. J., **Hamill, J.** Kinematic adaptations during running: footwear, surface and duration consequences. *Medicine and Science in Sports and Exercise*, 36(5):838-844, 2004.
- Van Emmerik, R.E.A., Rosenstein, M.T., McDermott, W.J., **Hamill, J.** Nonlinear Dynamical Approaches to Human Movement. *Journal of Applied Biomechanics*, 20:396-420, 2004.
- Pollard, C.D., McClay Davis, I., **Hamill, J.** Influence of gender on hip and knee mechanics during a randomly cued cutting maneuver. *Clinical Biomechanics* 19:1022-1031, 2004.
- O'Connor, K.M., **Hamill, J.** Frontal plane moments do not accurately reflect ankle dynamics during running. *Journal of Applied Biomechanics* 21:85-95, 2005.
- Van Emmerik, R.E.A., **Hamill, J.**, McDermott, W.J. Variability and coordinative function in human gait. *Quest* 57:108-129, 2005.
- Pollard, C.D., Heiderscheit, B.C., Van Emmerik, R.E.A., **Hamill, J.** Gender differences during an unanticipated cutting maneuver. *Journal of Applied Biomechanics* 21:143-152, 2005.
- Manal, K., Chang, Ch-C., **Hamill, J.**, Stanhope, S.J. A three-dimensional data visualization technique for reporting movement pattern deviations. *Journal of Biomechanics* (in press), 2005.
- O'Connor, K.M., Price, T.B., **Hamill, J.** Examination of extrinsic foot muscles during running using mf MRI and EMG. *Journal of Electromyography and Kinesiology* (in press), 2005.

Li, L., Haddad, J., **Hamill, J.** Stability and variability may respond differently to changes in walking speed. *Human Movement Sciences* (in press), 2005.

Haddad, J., Van Emmerik, R.E.A., Whittelsey, S.N., **Hamill, J.** Adaptations in interlimb and intralimb coordination to asymmetrical loading in human walking. *Gait and Posture* (in press), 2005.

MANUSCRIPTS UNDER REVIEW

Hardin, E., **Hamill, J.** The influence of shoe/surface interactions on impact shock attenuation. *Journal of Sports Science*, 2005.

Milner, CE, Davis, IS, **Hamill, J.** Free moment as a predictor of tibial stress fracture in distance runners. *Journal of Biomechanics*, 2005

MacLean, C, Davis, IS, **Hamill, J.** Influence of a Custom Foot Orthotic Intervention on Lower Extremity Dynamics in Healthy Runners. *Clinical Biomechanics*, 2005.

Milner, CE, Ferber, R., Pollard, CD, **Hamill, J.**, Davis, IS. Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners. *Medicine and Science in Sports and Exercise*, 2005.

Zifchock, RA, Davis, IS, **Hamill, J.** Kinetic asymmetry in female runners with and without retrospective tibial stress fractures. *Journal of Biomechanics*, 2005

MANUSCRIPTS IN PREPARATION

Derrick, T. R., Caldwell, G. E., Hamill, J. The effect of simulated MUAP shape, rate and variability on the power spectrum.

Hamill, J., Derrick, T. R. Co-contraction of lower extremity muscles under varying stride frequency conditions.

Hamill, J., Derrick, T.R., McClay, I. Joint stiffness during running with different footfall patterns.

PROCEEDINGS

Bates, B. T., Sawhill, J. A., **Hamill, J.** Dynamic running shoe evaluation. In Proceedings of Human Locomotion, Special Conference of the Canadian Society of Biomechanics, 122-124, London, Ontario, October, 1980.

Hamill, J., Bates, B. T., White, C. A. Evaluation of foot orthotic appliances using ground reaction force data. In Proceedings of Human Locomotion II, Special Conference of the Canadian Society of Biomechanics, 74-76, Kingston, Ontario, September, 1982.

Osternig, L. R., Sawhill, J. A., Bates, B. T., **Hamill, J.** Function of limb speed on torque patterns of antagonist muscles. In *Biomechanics VIII-A, International Series on Biomechanics, Vol. 4B*, H. Matsui and K. Kobayashi (eds.), 251-257, Human Kinetics Publishers, Champaign, IL, 1983.

Bates, B. T., Sawhill, J. A., **Hamill, J.**, Osternig, L. R. Identification of critical variables describing ground reaction forces during running. In *Biomechanics VIII-B, International Series on Biomechanics, Vol. 4B*, H. Matsui and K. Kobayashi (eds.), 635-640, Human Kinetics Publishers, Champaign, IL, 1983.

Hamill, J., Knutzen, K. M., Bates, B. T. Ambulatory consistency of the visually impaired. In *Biomechanics IX-A, International Series on Biomechanics, DA Winter, RW Norman, RP Wells, KC Hayes, AE Patla* (eds.), 570-575, Human Kinetics Publishers, Champaign, IL, 1985.

Bates, B. T., **Hamill, J.**, Morrison, E. A comparison between forward and backward running. In *Proceedings of the Olympic Scientific Congress*, M. Adrian and H. Deutsch (eds.), 127-136, Microform Publications, Eugene, OR, 1986.

Knutzen, K. M., **Hamill, J.** Evaluation of ankle taping and bracing influences during the support phase of running. In *Proceedings of the Olympic Scientific Congress*, M. Adrian and H. Deutsch (eds.), 151-158, Microform Publications, Eugene, OR, 1986.

Smith, P. K., **Hamill, J.** Selected karate and boxing glove impact characteristics during the punch. In *Proceedings: Third International Society of Biomechanics in Sport Symposium*, J. Terauds and J. Barham (eds.), 114-122, Academic Publishers, CA, 1986.

Hamill, J., Golden, D. M., Ricard, M. D., Williams, M. A. Dynamics of selected tower dive take-offs. In *Proceedings: Third International Society of Biomechanics in Sport Symposium*, J. Terauds and J. Barham (eds.), 200-207, Academic Publishers, CA, 1986.

Holt, K. G., **Hamill, J.**, O'Connor, D. Effects of orthotic inserts adjusted for walkers with rearfoot dysfunction. In *Proceedings of Fifth Biennial Conference of the Canadian Society of Biomechanics*, 80-81, Ottawa, Canada, 1988.

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If the shoe fits: A biomechanical analysis of locomotion. Sigma Xi Society, University of Massachusetts, Amherst, MA, November 16, 1988.

Muscle soreness during running: Biomechanical and physiological considerations. Neuromuscular Research Center Seminar, Boston University, September 20, 1989.

Design of athletic shoes : Biomechanical considerations. Kinesiology Academy Meeting at the American Alliance of Health, Physical Education, Recreation, and Dance Annual Meeting, New Orleans, LA, April 28, 1990.

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A case study of a patient with patellofemoral pain. Eugene Michaels Lecture at the Combined Sections Meeting of the American Physical Therapy Association Annual Meeting, Dallas, Texas, February 14, 1997.

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Shock attenuation and transmission during running. (with T. R. Derrick). XVIIth Congress of the International Society of Biomechanics, Calgary, Alberta, Canada, August 12, 1999.

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Mechanical models and human locomotion. Beijing University, China, October 18, 2001.

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Is There a Gender Bias in Anterior Cruciate Ligament Injuries? Departments of Physical Therapy and Exercise and Sports Science, East Carolina University, Greenville, NC, October 16, 2003.

Future Direction in Biomechanics Doctoral Education. Biomechanics Academy, New Orleans, Louisiana, April 2, 2004.

Footwear in athletics. University of Staffordshire Graduate Seminar, Stoke on Trent, UK, April 21, 2004.

The Gender Bias in Anterior Cruciate Injuries. Seventh International Conference on Foot Biomechanics and Orthotic Therapy, Boston, MA October 29, 2004.

Is there a Gender Bias in Lower Extremity Injuries? Department of Sports Science, University of Edinburgh, Edinburgh, Scotland, December, 2004.

Biomechanics, Exercise Physiology and the 75th Anniversary of the Research Quarterly for Exercise and Sports, American Alliance of Health, Physical Education, Recreation and Dance Annual meeting, Chicago, IL, April 19, 2005.

EXTERNAL FUNDING

Grants

1. Dynamics of platform diving, United States Diving Association, \$3,000, 1/1984 - 12/1984. 9/1985 - 6/1986.
2. Effects of anatomically variant foot-types on walking gait, ORDA, Southern Illinois University, \$6,000,
3. Effect of orthotic inserts on walkers with rearfoot and forefoot dysfunctions. Biomedical Research Support Grant, University of Massachusetts, \$6,000, 1/1987 - 1/1989.
4. Activity in later life: effects on posture and gait. National Institute of Aging, co-principal investigator, resubmitted January 28, 1988 (approved but not funded).
5. Musculoskeletal fitness norms for individuals aged 45-75. National Institute of Health, submitted February 1, 1988 (approved but not funded).
6. Mechanics of springboard diving: Modeling the diver-board system, United States Diving Association, \$15,000, 1/1989 - 1/1991.
7. Biomechanical analysis of military boots, (Grant #DAAK60-91-C-0102) U.S. Army, Natick, MA, \$183,000, 7/1991 - 12/1992.
8. Biomechanical analysis of military boots, (Grant #DAAK60-95-R-8010) U.S. Army, Natick, MA, (with Wellco Industries, North Carolina), \$51,436, 9/1995 - 12/1997.

9. Biomechanical analysis of military boots: Phase III, (Grant #DAAK60-95-R-8010) U.S. Army, Natick, MA, (with Wellco Industries, North Carolina), \$5,000, 9/1999 - 12/1999.
10. Biomechanical analysis of military boots. (Contract #DAAK16-00-P-0112) U.S. Army Soldier Systems Center, Natick, MA, \$25,000, 1/2000 - 6/2000.
11. Prospective study on tibial stress fractures. (Grant # DAMD17-00-1-0515), Department of the Army, (with Irene McClay). \$1,050,000, 8/1/2000 – 8/1/2004.

Contracts

1. Mechanics of lower extremity function, Isotechnologies, Inc., \$12,000, 9/1982 - 6/1984.
2. Ergonomics of lower extremity function, KangaROOS, USA, \$58,000, 9/1986 - 9/1989.
3. Prophylactic Knee and Ankle Bracing, AirCast Corp., \$20,000, 9/1988 - 9/1989.
4. Lower extremity action during exercise, Life-Fitness Group, \$6,000, 7/1990 - 7/1992.
5. Lower extremity mechanics, Hyde Athletic Shoe Company, \$279,000, 1/1989 - 1/1997.
6. Biomechanical analysis of golf equipment, Titleist and Footjoy Worldwide, \$283,000, 6/1992-12/1997.
7. Biomechanical analysis of hiking gait, The Timberland Company, \$15,000, 3/1995 - 10/1995.
8. A physiological profile of the game of field hockey. (with P. S. Freedson). United States Olympic Committee, Colorado Springs, Colorado, \$35,132, 1/1996 - 12/1996.
9. Locomotor patterns on running machines. NordicTrak, \$10,000, 9/1997-3/1998.
10. Plantar pressure patterns during hiking gait. The Timberland Company, \$42,000, 3/1998 - 5/1999.
11. Investigation of foot scaling using a 3-D laser measurement system. Titleist and FootJoy Worldwide, \$50,000, 1/1999 – 12/2000
12. Biomechanical analysis of golf footwear, Titleist and FootJoy Worldwide, \$63,000, 1/1999-12/1999.
13. Walking and running mechanics and their effect on footwear, Hyde Athletic Shoe Company, \$33,000, 1/1999 - 12/1999.

14. In-shoe temperatures during hiking, The Timberland Company, \$15,000, 1/1999-3/1999.
15. Plantar forces during basketball movements, And1 Company, \$15,000, 1/1999-3/1999.
16. Rearfoot motion and shock attenuation in trail running footwear, The Timberland Company, \$10,000, 6/1999-7/1999.
17. Running mechanics and their effect on footwear. Hyde Athletic Shoe Company, \$33,000, 1/2000 - 12/2000.
18. Implementation of a 3-D laser measurement system. Titleist and FootJoy Worldwide, \$89,000, 1/2000 – 12/2000.
19. Shock attenuation in hiking footwear. The Timberland Company, \$18,000, 1/2000 – 6/2000.
20. Traction analysis of golf footwear. Titleist and FootJoy Worldwide, \$48,000, 1/2000 – 12/2000.
21. Prospective study on tibial stress fractures. (with Irene McClay). US Army, \$1,050,000, 8/1/2000 – 8/1/2004.
22. Footwear Testing. Titleist and FootJoy Worldwide. \$50,000, 1/2001 - 12/2001.
23. 3-D laser measurement system. Titleist and FootJoy Worldwide, \$89,000, 1/2001 – 12/2001.
24. Walking mechanics and their effect on footwear. Hyde Athletic Shoe Company, \$33,000, 1/2001 - 12/2001.
25. Modeling Parachute Landing Falls. Sub-contract from Foster-Miller, Inc., Waltham, MA, \$85,000, 1/2001 – 8/2003.
26. A new 3-D laser measurement system. Titleist and FootJoy Worldwide, \$69,000, 1/2002 –

12/2002.

- 12/2002. 27. Footwear Testing. Titleist and FootJoy Worldwide, \$50,000, 1/2002 - 12/2002.
28. Footwear Testing. Hyde Athletic Shoe Company, \$16,500, 1/2002 - 6/2002.
29. Footwear Testing, Timberland Company, \$24,000, 1/2002 – 12/2002.
- 12/2003. 30. Footwear Testing. Titleist and FootJoy Worldwide, \$124,000, 1/2003 - 12/2003.
31. Footwear Testing, Timberland Company, \$24,000, 1/2003 – 12/2003.
32. Footwear Testing. Acushnet Company, \$60,000, 1/2004 - 12/2004.
33. Footwear Testing. Acushnet Company, \$60,000, 1/2005 - 12/2005.

Appendix E

Articles accepted or submitted for publication (see PDFs attached).

Milner, CE, Davis, ID and Hamill, J. (2006) Relationship between free moment and tibial stress fractures. (in press) Journal of Biomechanics.

Milner, CE, Davis, ID, Ferber, R, Pollard, CD & Hamill, J (2006). Biomechanical factors associated with tibial stress fractures in female runners. Med Sci Sport and Ex.38, 323-328

Davis, IS (2005). Gait Retraining in Runners. Orthopedic Physical Therapy Practice, 17(2)8-13.

Milner, CE, Hamill, J and Davis, IS (2006) Does loading during early stance contribute to tibial stress fractures? (in review) Journal of Bone and Joint Surgery.

Does loading during early stance contribute to tibial stress fractures?

Clare Milner, PhD, Joseph Hamill, PhD, & Irene Davis, PhD, PT

Abstract

Tibial stress fractures (TSF) are a serious overuse injury in runners. Higher vertical loading rates have been found in runners with previous TSF compared to controls, alongside higher tibial shock. Since peak tibial shock occurs very early in stance phase, conditions at footstrike may be important in determining its magnitude. The purpose of this cross-sectional study was to identify lower extremity biomechanics that may contribute to high tibial shock. Twenty three rearfoot strikers with a history of tibial stress fracture and 23 age and mileage matched rearfoot striking control subjects with no previous lower extremity bony injuries participated in this study. Gait data were collected at 120 Hz (960 Hz analog) as subjects ran at 3.7m/s on a 25m runway. Independent t-tests and effect size (ES) were used to investigate the hypothesized differences between the groups. Pearson Product Moment correlations were used to determine whether initial contact variables were related to tibial shock. Runners with a previous TSF had significantly higher sagittal plane knee joint stiffness than controls. Stiffness was positively and moderately correlated with shock. Knee excursion and shank angle at footstrike were negatively and moderately correlated with shock. Small effects with moderate correlations for excursion and shank angle suggest that pose of the leg during initial contact is less important than sagittal plane knee joint stiffness.

Introduction

Tibial stress fractures (TSF) are a serious overuse injury in runners. This bony injury typically requires up to 6 to 12 weeks of functional rehabilitation for full recovery (Harmon, 2003; Tuan et al., 2004) TSF is typically the most common stress fracture in runners, accounting for 26% to 45% of stress fractures (Bennell et al., 1996; Bruckner et al., 1996). Recent evidence from a comparison of runners with and without previous TSF suggests a predictive relationship between high tibial shock and TSF (Milner et al., 2006a). Additionally, it has been suggested that torsional loading may be important in the occurrence of TSF in distance runners (Milner et al., 2006b). Furthermore, recent in vivo studies in bovine tibiae indicate that microcrack propagation as a result of torsional loading increases when the torsional loading is preceded by axial compression of the bone (Wang et al., 2005). Hennig et al (1993) found that tibial shock was related to vertical ground reaction force loading rates. Milner et al (2006a) found higher vertical loading rates in runners with previous TSF compared to controls, alongside higher tibial shock, further supporting this relationship.

However, it appears that this relationship can be modified by changes in lower extremity kinematics during running, specifically knee flexion angle. “Groucho running” was described by McMahon et al (1987) as running with exaggerated knee flexion throughout the stance phase. When six runners performed Groucho running on a treadmill, higher tibial shock compared to normal running was observed, but no change in impact peak. While the modeled mean lower extremity stiffness for the entire stance phase was lower with Groucho running, stiffness of individual joints at the period just after footstrike,

when peak tibial shock occurs, was not determined. In particular, knee joint stiffness may affect peak shock, since the knee is the major contributor to sagittal plane lower extremity stiffness. Furthermore, Milner et al (2006a) found a moderately higher mean sagittal plane knee joint stiffness from footstrike to peak knee flexion in runners with previous TSF. Lower sagittal plane knee joint stiffness during early stance may result in greater attenuation of shock and, therefore, be related to lower peak tibial shock. Knee flexion excursion is the kinematic component of sagittal plane knee joint stiffness, therefore, it may also be lower in runners with lower tibial shock.

Since peak tibial shock occurs very early in stance phase, conditions at footstrike may be important in determining its magnitude. Derrick (2004) presented experimental data indicating that very small increases in knee flexion angle at foot strike are associated with very small increases in tibial shock. Sagittal plane knee joint stiffness data were not reported. The knee angle at footstrike was interpreted as providing support for an effective mass model which suggests an inverse relationship between sagittal plane knee joint stiffness and peak shock. The author assumed a positive relationship between knee angle at foot strike and knee joint stiffness. Nevertheless, these data suggest that kinematic conditions during early stance may influence peak tibial shock. In particular, the increased knee flexion angle reported by Derrick (2004) may reflect a more vertical shank position at footstrike. A more vertical shank would more closely align the long axis of the tibia with the large vertical component of the ground reaction force, thus increasing the magnitude of tibial shock, which is related to the vertical component of ground reaction force (Hennig et al., 1993).

Recent studies of variability during running have divided the stance phase into four subphases based on discrete ground reaction force events (e.g. Ferber et al., 2005). These divisions are based on the changing function of the lower extremity across the stance phase. The first phase, from foot contact to impact peak, is referred to as ‘initial loading’, since the stance limb is rapidly accepting body weight. This phase typically occurs during the first 20% of stance. During initial loading, vertical loading rates are at their highest. Peak tibial shock also occurs around this time. Therefore, lower extremity mechanics during initial loading may be related to peak tibial shock. If so, they may be associated with an increased risk of tibial stress fracture. Identification of these mechanics is the first step in the development of strategies to reduce tibial shock and, potentially, the risk of TSF in runners.

The purpose of this cross-sectional study was to identify lower extremity biomechanics that may contribute to high tibial shock. In particular, the aim was to determine whether differences existed in initial loading mechanics between distance runners with a history of TSF and those with no previous lower extremity bony injuries. We hypothesized that runners with a previous TSF would have higher sagittal plane knee joint stiffness (KSTIF) and lower knee flexion excursion (KEXC) during the initial loading phase and a more vertical shank at footstrike (SHKFS) than runners who had not sustained a fracture. We also hypothesized that there would be a positive correlation between knee stiffness and peak tibial shock (TIBSHK) and negative correlations between KEXC and TIBSHK and SHKFS and TIBSHK across the sample as a whole.

Methods

Approval for all procedures was obtained from the Institution's Human Subjects Review Board prior to commencing this study. All participants gave their written informed consent prior to participating. Female runners aged between 18 and 45 years and running at least 32 km per week on average were recruited from the local running population. Subjects were excluded if they injured, had a history of cardiovascular pathology, had abnormal menses (missed more than 3 consecutive monthly periods in the previous 12 months), were pregnant or suspected they were pregnant. Twenty three rearfoot strikers with a history of tibial stress fracture (TSF: age 25 ± 8 y, 47 ± 14 km per week) and 23 age and mileage matched rearfoot striking control subjects with no previous lower extremity bony injuries (CTRL: age 24 ± 9 y, 46 ± 15 km per week) participated in this study. On entry into the study, the TSF group had reported a previous tibial stress fracture, which had been confirmed at the time by a medical professional using diagnostic imaging tests (bone scan, MRI or x-ray).

A priori power calculations for this study were done using preliminary data from our laboratory for knee flexion excursion from footstrike to peak knee flexion. Sample size was determined based on predicted power to detect a difference of 15% between the groups with an alpha 0.05 and 80% power. We considered a difference of 15% or more to be clinically relevant. Based on calculations made in Samplepower (SPSS Inc, Chicago, IL), a minimum sample size of 19 subjects per group was indicated. Therefore, inclusion of 23 subjects per group should provide adequate power to detect clinically relevant differences in all variables between groups. Additionally, the power to detect a significant

moderate correlation of 0.5 between variables was assessed using the Samplepower software. It was determined that 26 subjects would be needed to detect a moderate correlation across the groups with an alpha 0.05 and 80% power. Given that pooling the two groups would yield 40 subjects, the study should have more than adequate power to detect a moderate correlation between variables.

Lower extremity three-dimensional position data were collected at 120 Hz using a six camera Vicon 512 system (Oxford Metrics, Oxford, UK) while the subject ran across a force platform (Bertec Corporation, Columbus, OH) embedded in the middle of a 23 m runway. Subjects completed five good trials, in which their test limb contacted the middle of the force platform without targeting, while instrumented with retroreflective tracking markers and a uniaxial accelerometer. The force platform and accelerometer were synchronized to the kinematic data collection and sampled at 960 Hz. Participants ran at $3.7 \text{ m/s} \pm 5\%$; running velocity was monitored via two photocells which triggered a timer. Subjects wore standard neutral laboratory running shoes. In addition, a standing calibration trial was taken, with additional anatomical markers attached to the limb, to enable determination of segment coordinate systems. Data were collected from the involved limb in the TSF group and the right limb in the CTRL group, since we had no reason to prefer a particular side in the CTRL group.

Molded thermoplastic shells with four non-collinear markers attached were secured on the postero-lateral proximal thigh and postero-lateral distal shank. Three markers were attached to the heel portion of the running shoe to approximate rearfoot motion: two marking the vertical bisection of the heel and a third on the lateral side of the heel. Several additional anatomical markers were attached to the subject initially to

define the anatomical coordinate systems and inertial parameters of each segment. These were removed following the standing calibration trial. Anatomical markers were placed over the greater trochanter, lateral and medial knee at the level of the lateral femoral epicondyle, lateral and medial ankle at the level of the lateral malleolus, first and fifth metatarsal heads and the tip of the toe box.

Data were processed in Visual 3D (C-Motion, Rockville, MD). Three-dimensional ankle and knee angles were resolved about a Joint Coordinate System (Grood and Suntay, 1983). Kinetic data, used in the calculation of joint stiffness, were calculated about XYZ rotation Cardan angles referenced to coordinate systems embedded in the distal segment. All other variables were calculated using custom LabView (National Instruments Corporation, Austin, TX) programs. Marker trajectories were low-pass filtered at 8 Hz and kinetic data were low pass filtered at 50 Hz using fourth order Butterworth filters. The timing of the vertical impact peak was used to define the initial contact period of interest: from foot strike to impact peak (Ferber et al., 2005). TIBSHK was calculated after the average value over the stance phase was removed. TIBSHK was determined as the highest positive acceleration measurement during the stance phase.

Knee flexion excursion (KEXC) was calculated as knee flexion range of motion during initial contact. Average knee flexion stiffness was calculated as the change in joint moment divided by the change in joint angle (Farley and Gonzalez, 1996) during initial contact. It is recognized that this stiffness measure represents the sum of many individual stiffnesses and may, more accurately, be referred to as measures of quasi-stiffness (Latash and Zatsiorsky, 1993). However, for the purposes of this paper, the term stiffness will be used. All subject were confirmed as rearfoot strikers using strike index, as

described by Cavanagh and LaFortune (1980). All variables were determined for each of five trials per subject, averaged within the subject and then averaged across groups.

Boxplots were used to identify extreme outliers, defined as values more than three times the interquartile range away from the interquartile range. Identified extreme outliers were removed from the data before statistical analysis of the differences between groups. One data point fell outside this defined range and was removed from the RTSF group for KSTIF. Independent t-tests were used to test for significant differences between groups, based on the hypotheses stated previously. In addition, effect sizes were determined for between-group comparisons to aid in the interpretation of these data. Bivariate correlations were made between TIBSHK and the variables of interest across the whole sample. The alpha level for all statistical tests was 0.05.

Results

Runners with a previous TSF had significantly higher sagittal plane knee joint stiffness than CTRL (Table 1); this moderate effect was as expected based on our hypotheses. However, KEXC and SHKFS were not significantly different between the groups. Furthermore, the small effect size for these variables supports this result. Correlations between these variables and TIBSHK across the whole sample reflected these between group observations (Figures 1 to 3). All three correlations were significantly different from zero in the direction hypothesized and all were moderate (KSTIF 0.406; KEXC -0.418; SHKFS -0.317). KSTIF was positively correlated with TIBSHK, with higher stiffness being related to higher shock. KEXC and SHKFS were both negatively

correlated with TIBSHK, with smaller knee flexion excursion and a more vertical shank angle at foot strike being related to higher shock.

Discussion

We hypothesized that several lower extremity kinematic characteristics may be related to high tibial shock. Knee stiffness during the initial loading phase of stance was positively correlated with tibial shock in distance runners. Furthermore, those runners with a previous TSF, linked to higher TIBSHK in a previous study (Milner et al., 2006a), had significantly higher sagittal plane knee joint stiffness than runners with no lower extremity bony injuries. This relationship was as hypothesized and appears to be contradictory to earlier studies that have indicated that lower stiffness is related to higher TIBSHK. However, on closer examination, there are important differences between the present study and these existing studies.

The study of Groucho running (McMahon et al, 1987) required runners to grossly alter their natural running gait to one of increased knee flexion while running on a treadmill. This unnatural gait may not be representative of inter-individual differences within the range of lower extremity kinematic patterns that occur in unconstrained running overground at a given speed. Furthermore, McMahon et al. (1987) modeled stiffness of the entire lower extremity over the whole of the stance phase. Since the dynamic function of the contact limb changes across the stance phase from footstrike and initial loading through full weight acceptance to propulsion and toe-off, important differences within a sub-phase may be masked when considering stance as a single event. In addition, lower

extremity stiffness is a compound measure modeled as a mass-spring system based on the thigh angle at midstance to estimate the net stiffness of the hip, knee and ankle joints. Therefore, important differences at individual joints may be masked in this model.

The more recent work by Derrick (2004) on effective mass suggested that TIBSHK would be higher when the shank-foot complex was free to move independently of the rest of the body, i.e. with lower knee joint stiffness. The concept of effective mass states that tibial acceleration (TIBSHK) will be higher when the effective mass to be accelerated is smaller. Essentially, the effective mass of the shank-foot complex is reduced by decreasing knee joint stiffness. The smaller effective mass can be accelerated more easily, resulting in higher segment acceleration (TIBSHK). However, data provided to support the argument did not include knee joint stiffness or even knee joint excursion, a component of knee joint stiffness. Only knee flexion angle at footstrike was presented. The correlation between knee flexion angle at footstrike and sagittal plane knee joint stiffness in the present sample was moderate at 0.336. However, there was no significant correlation between knee flexion angle at footstrike and TIBSHK in this sample. This suggests that knee flexion angle at footstrike accounts for around 11% of KSTIF and is not related to peak tibial shock during running. In addition, we found KSTIF to positively correlated to TIBSHK, with higher joint stiffness being related to higher TIBSHK. The results of the present study do not support the effective mass hypothesis.

KEXC is a component of KSTIF and showed a similar moderate correlation with TIBSHK. However, no difference between the TSF and CTRL groups was found for

KEXC; KEXC also had only a small effect size. This suggests that KSTIF is a better discriminator of runners with previous TSF. This difference between KEXC and KSTIF also indicates that kinematic data alone do not fully describe the status of the knee during initial loading in relation to TSF. In addition, and contrary to expectations, SHKFS did not discriminate between the groups. It was hypothesized that a smaller shank angle, that is the shank being closer to the vertical, would be related to a higher tibial shock and so be higher in the TSF group. While a moderate correlation with TIBSHK was found, no difference was observed between the groups and the variable had only a small effect size.

In summary, sagittal plane knee joint stiffness is moderately correlated with peak tibial shock in runners. Furthermore, knee joint stiffness is higher in runners with a previous tibial stress fracture compared to runners with no previous lower extremity bony injuries. Small effects with moderate correlations for KEXC and SHKFS suggest that pose of the leg during initial contact is less important than sagittal plane knee joint stiffness.

Acknowledgements

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Table 1: Initial loading variables of interest in runners with a previous tibial stress fracture (TSF) and a matched control (CTRL) group

	KSTIF*	KEXC (°)	SHKFS (°)
TSF	0.044 ± 0.021	14.4 ± 4.0	12.8 ± 3.4
CTRL	0.030 ± 0.015	16.0 ± 5.3	14.1 ± 3.3
<i>P</i>	0.015	0.252	0.181
ES	0.79	0.36	0.40

KSTIF is change in normalized joint moment (Nm/(mass in kg x height in m)) divided by change in joint angle

*significant difference at $P \leq 0.05$ level

Figure 1: Scatterplot of sagittal plane knee joint stiffness (KSTIF) against peak tibial shock (TIBSHK) in runners with a previous tibial stress fracture (TSF) and a matched control (CTRL) group

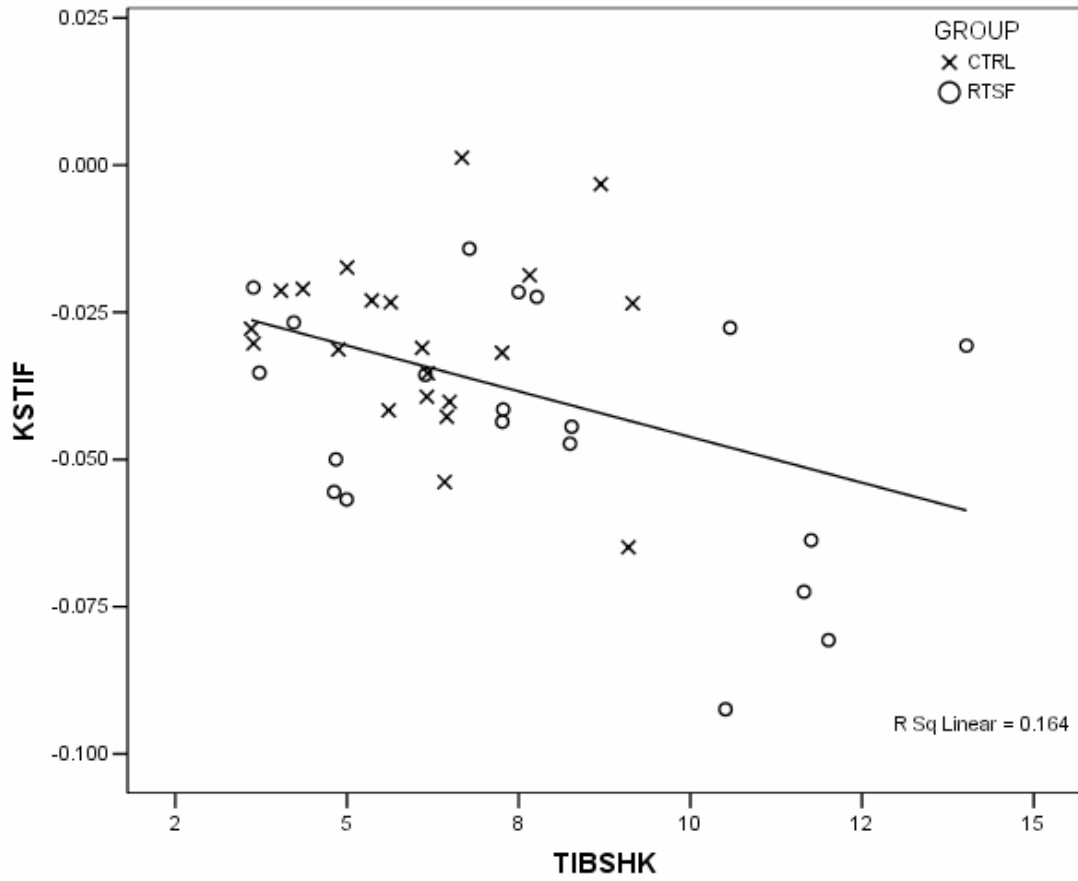


Figure 2: Scatterplot of knee flexion excursion (KEXC) against peak tibial shock (TIBSHK) in runners with a previous tibial stress fracture (TSF) and a matched control (CTRL) group

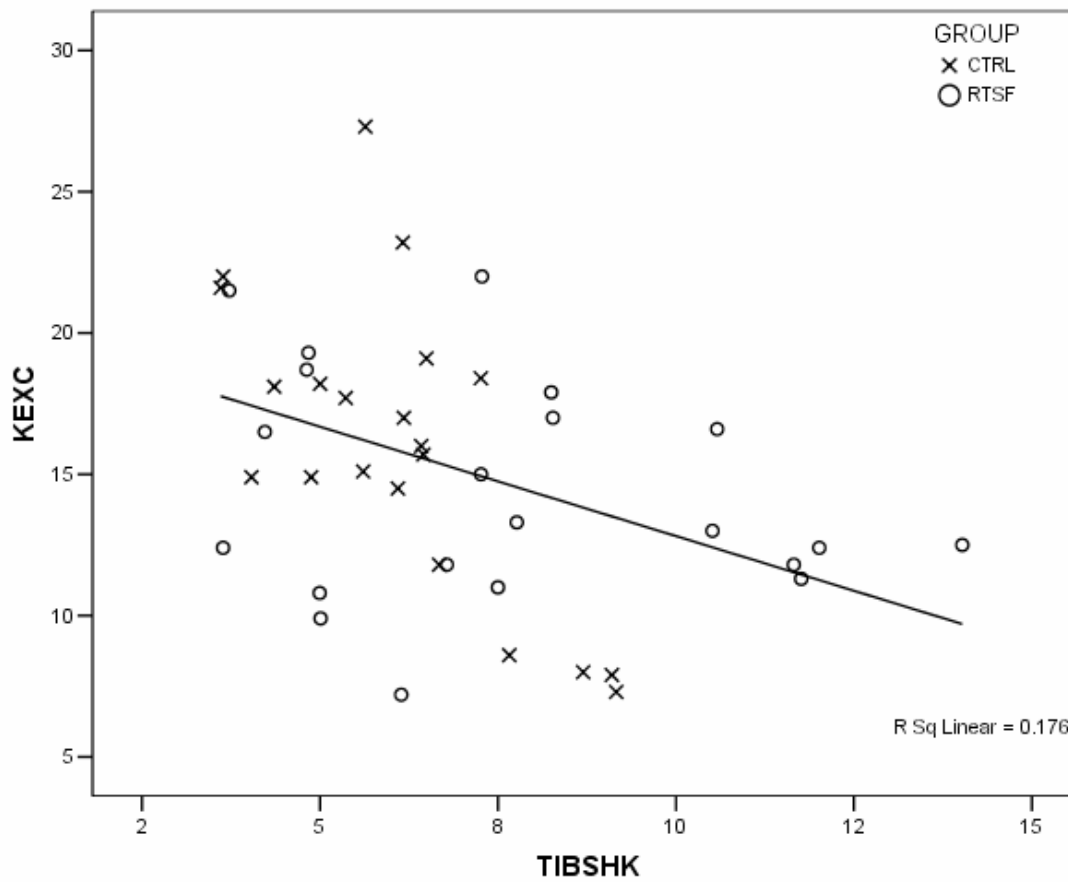
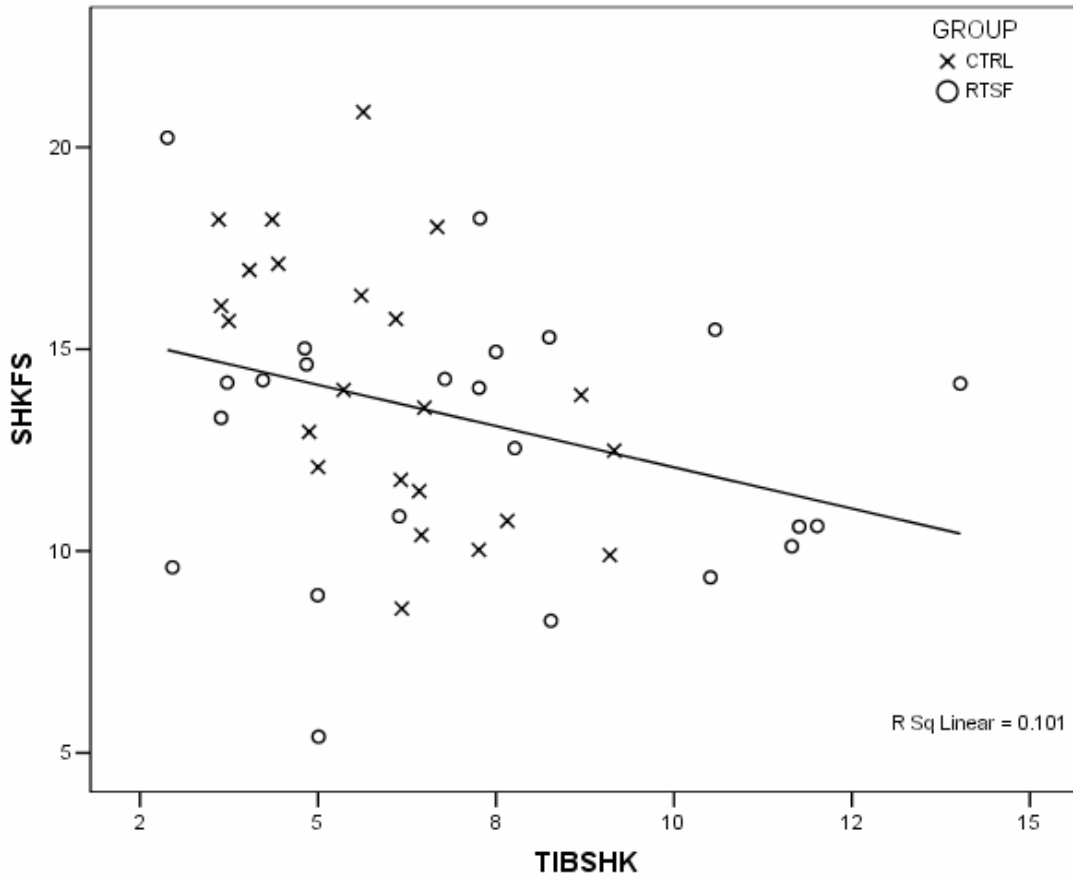


Figure 3: Scatterplot of sagittal plane shank angle at footstrike (SHKFS) against peak tibial shock (TIBSHK) in runners with a previous tibial stress fracture (TSF) and a matched control (CTRL) group



Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners

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¹Department of Physical Therapy, University of Delaware, Newark, DE; ²Faculty of Kinesiology, University of Calgary, Calgary, Alberta, CANADA; ³Department of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, CA; and ⁴Department of Exercise Science, University of Massachusetts, Amherst, MA

ABSTRACT

MILNER, C. E., R. FERBER, C. D. POLLARD, J. HAMILL, and I. S. DAVIS. Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners. *Med. Sci. Sports Exerc.*, Vol. 38, No. 2, pp. 323–328, 2006. **Purpose:** Tibial stress fractures (TSF) are among the most serious running injuries, typically requiring 6–8 wk for recovery. This cross-sectional study was conducted to determine whether differences in structure and running mechanics exist between trained distance runners with a history of prior TSF and those who have never sustained a fracture. **Methods:** Female runners with a rearfoot strike pattern, aged between 18 and 45 yr and running at least 32 km·wk⁻¹, were recruited for this study. Participants in the study were 20 subjects with a history of TSF and 20 age- and mileage-matched control subjects with no previous lower extremity bony injuries. Kinematic and kinetic data were collected during overground running at 3.7 m·s⁻¹ using a six-camera motion capture system, force platform, and accelerometer. Variables of interest were vertical impact peak, instantaneous and average vertical loading rates, instantaneous and average loading rates during braking, knee flexion excursion, ankle and knee stiffness, and peak tibial shock. Tibial varum was measured in standing. Tibial area moment of inertia was calculated from tibial x-ray studies for a subset of runners. **Results:** The TSF group had significantly greater instantaneous and average vertical loading rates and tibial shock than the control group. The magnitude of tibial shock predicted group membership successfully in 70% of cases. **Conclusion:** These data indicate that a history of TSF in runners is associated with increases in dynamic loading-related variables. **Key Words:** GROUND REACTION FORCES, KINEMATICS, TIBIAL SHOCK, AREA MOMENT OF INERTIA

Stress fractures are a common injury in runners. They are consistently among the five most common running injuries, and account for 50% of all injuries sustained by runners and military recruits (13,14,19). The overall incidence of stress fractures ranges from 1.5 to 31% (13,14,19,22,26). Women are reported to be at significantly greater risk, with one study reporting a twofold increase of bilateral stress fractures over men (25). Similarly, the incidence of stress fractures in women college athletes was

double that of men at a Division I institution (1). Others have reported an even greater gender bias in the incidence of stress fractures. An increased incidence of stress reactions, a precursor to stress fracture (8), by a factor of 2.91 in women compared with men has been reported in military recruits (26). The tibia is the most common site of stress fractures in runners, accounting for between 33 and 55% of total stress fractures reported (3,9,18,25,28).

Bone structure is thought to contribute significantly to the overall risk of tibial stress fractures (TSF). This has been shown to be the case in both male military recruits (22) and male runners (5), but not female runners (10). Mediolateral tibial width (9) and tibial area moment of inertia (22) are smaller in those male military recruits who go on to develop a stress fracture. In addition, tibial cross-sectional area, a strong determinant of area moment of inertia, is also smaller in male runners with a history of stress fracture (5). The relationship between tibial area moments of inertia and stress fracture has not been

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determined for female runners. Tibial cross-sectional area, however, was not linked to the occurrence of TSF in a study of 13 female runners with a history of stress fracture (2).

Anatomic alignment has also been implicated in the cause of lower extremity stress fractures. Matheson et al. (18) noted that varus malalignment (genu, tibial, subtalar, and forefoot varus) was often present in athletes with lower extremity stress fractures. During running, the body experiences vertical forces between 2.5 and 2.8 times body weight (23). During this compressive loading, a tibia in varus will likely experience greater bending moments as the vertical force vector projects medial to the tibial shaft. This can result in greater susceptibility to TSF.

Stress fractures are thought to be related to some quantity, or “dose” of loading, where dose may be a measure of some combination of peak shock, ground reaction force loading rates, peaks, and repetitions. Some researchers, however, have reported no difference in vertical impact and active peak ground reaction forces between runners with and without a history of TSF (2,5). Conversely, Grimston et al. (10) reported significantly greater vertical impact and active forces in female runners with a history of tibial or femoral stress fractures compared with those without such a history. Increased ground reaction forces would likely result in greater bending moments experienced by the tibia. Furthermore, Hennig et al. (12) and Laughton et al. (16) both reported that vertical ground reaction force-loading rates were significantly and positively correlated to peak tibial accelerations during running. Therefore, if loading rates are increased, it is likely that tibial shock is also increased. Whether the increased loading rates are directly related to strain rates experienced by the bone is yet to be determined. However, preliminary work in our laboratory (6) suggests, that increased loading rates can be related to tibial stress fracture in female distance runners.

Although smaller in magnitude, anterior–posterior ground reaction forces applied to the lower extremity during the loading phase of stance may also influence loading of the tibia. Previous studies have again produced conflicting results. Runners with a history of TSF have demonstrated increased (10) and normal (2,5) peak braking force. Based on our preliminary work, which suggests that loading rates are significantly different between these groups with respect to vertical ground reaction forces (6), we expect loading rates during braking to also be increased in runners with a history of stress fracture.

The total range of motion the lower extremity undergoes during the loading phase of the gait cycle may influence the forces experienced by the body. Assuming a given impulse, greater excursions will likely result in lower peak ground reaction forces and possibly lower loading rates. McNitt-Gray et al. (21) demonstrated this principle by reporting that lower peak ground reaction forces and loading rates were associated with greater hip and knee flexion excursions in controlled landings in gymnasts. These increased excursions may, therefore, reduce the risk for stress fractures. McMahan et al. (20) have shown that

running with exaggerated knee flexion (Groucho running) reduces the effective vertical stiffness of the lower extremity and causes the runner to attenuate more shock between the shank and head, compared with normal running. Conversely, if knee joint excursion is decreased, greater lower extremity stiffness will likely result. A “stiff” runner has been shown to spend less time in contact with the ground (7) and attenuate less shock (20). This may also increase their risk of TSF. The torsional stiffness of an individual joint may provide additional insight into the differences between runners with and without a history of TSF.

This cross-sectional study was conducted to determine whether differences in structure and mechanics existed between trained female distance runners with a history of a prior TSF and those who had not sustained a fracture. We hypothesized that runners who had a prior TSF would have increased vertical loading rates, increased vertical impact peak, increased loading rates during braking, and increased knee and ankle joint torsional stiffness in the sagittal plane, compared with those who had not sustained a fracture. Furthermore, we hypothesized that runners who had sustained a TSF would have increased tibial acceleration and decreased knee flexion excursion, compared with those who had not sustained a fracture. Structurally, they would have increased tibial varum during standing and decreased tibial area moment of inertia. Additionally, we hypothesized that the magnitude of tibial shock would discriminate between runners with and without a history of TSF.

METHODS

Subjects. Approval for all procedures was obtained from the human subjects review board of the University of Delaware before commencing this study. All subjects gave their written informed consent before participation in the study. Participants aged between 18 and 45 yr, who typically ran at least $32 \text{ km}\cdot\text{wk}^{-1}$, were recruited from local races, running clubs, and university cross-country teams by direct contact with study personnel or via flyers outlining the study. Subjects were excluded if they were currently injured, had a history of cardiovascular pathology, had abnormal menses (defined as missing more than three consecutive monthly periods in the last 12 months), or were pregnant or suspected they were pregnant. Runners with abnormal menses were excluded to reduce the likelihood of stress fractures being related to reduced bone density, rather than factors associated with running. A total of 20 rearfoot strikers with a history of tibial stress fracture (TSF: age 26 ± 9 yr, $46 \pm 11 \text{ km}\cdot\text{wk}^{-1}$, 35 ± 28 months after injury) and 20 age- and mileage-matched rearfoot striking control subjects with no previous lower extremity bony injuries (CTRL: age 25 ± 9 yr, $47 \pm 16 \text{ km}\cdot\text{wk}^{-1}$) participated in this study. These data are part of a larger study of distance runners, and those with a rearfoot strike pattern, confirmed by calculation of the strike index (4), were selected from the subject pool. On entry into the study, subjects reported their injury history. The TSF group had reported a previous TSF, which had been confirmed at

the time by a medical professional using diagnostic imaging tests (bone scan, magnetic resonance imaging (MRI), or x-ray study). Control runners had not reported any previous lower extremity bony injuries.

A priori power calculations for this study were done using preliminary data from our laboratory for peak tibial shock, instantaneous and average vertical loading rates, and knee flexion excursion. Sample sizes were determined based on predicted power to detect a difference of 15% between the groups with an alpha 0.05 and 80% power. We consider a difference of $\geq 15\%$ to be clinically relevant. Based on the formula of Lieber (17), minimal sample sizes of between 9 and 20 subjects per group were determined from our existing data for these variables. Inclusion of 20 subjects per group, therefore, should provide adequate power to detect clinically relevant differences in all variables between groups.

Kinematic and kinetic measurements. Lower extremity position data were collected at 120 Hz using a six-camera Vicon 512 motion capture system (Oxford Metrics, Oxford, UK). Markers were placed on the lower extremity and pelvic region to enable three-dimensional kinematics to be determined for the stance phase of running. A Bertec force platform (Bertec Corporation, Columbus, OH) synchronized with the motion capture system was used to collect ground reaction force data at 960 Hz. Additionally, a uniaxial accelerometer (PCB Piezotronics Inc, Depew, NY), also sampling at 960 Hz, was attached over the anteromedial portion of the distal tibia, as described by Lughton et al. (16). Running velocity was monitored via two photocells linked to a timer.

Markers were attached at L5S1, iliac crest and anterior superior iliac spine to track the pelvic segment. Molded thermoplastic shells with four noncollinear markers attached were secured on the posterolateral proximal thigh and posterolateral distal shank. Three markers were attached to the heel portion of the running shoe to approximate rearfoot motion: two marking the vertical bisection of the heel and a third on the lateral side of the heel. Several additional markers were attached to the subject initially to define the anatomic coordinate systems and inertial parameters of each segment. These markers were removed following the standing calibration trial. Anatomic markers were placed over the greater trochanter, lateral and medial knee at the level of the lateral femoral epicondyle, lateral and medial ankle at the level of the lateral malleolus, first and fifth metatarsal heads, and the tip of the toe box.

Subjects wore standard, neutral laboratory running shoes and ran overground along a 23-m runway at a velocity of $3.7 \text{ m}\cdot\text{s}^{-1}$ ($\pm 5\%$). Data were collected for a single stance phase as the runner traversed the force plate located in the center of the runway. Five acceptable trials were collected. Trials in which the subject appeared to change gait to target the force platform, as determined subjectively by the investigators, were discarded. Subjects performed practice trials to ensure that they could maintain a consistent running speed and make contact with the central portion of the force platform without modifying their gait.

Data were processed in Visual 3D (C-Motion, Rockville, MD). Three-dimensional ankle and knee angles were resolved about a joint coordinate system (11). Kinetic data, used in the calculation of joint stiffness, were calculated about XYZ rotation Cardan angles referenced to coordinate systems embedded in the distal segment. All other variables were calculated using custom LabView (National Instruments Corporation, Austin, TX) programs. Ground reaction force variables (vertical instantaneous and average loading rate (VILR, VALR), impact peak, (IPEAK), and anterior–posterior instantaneous and average loading rates during initial braking (BILR, BALR)) were determined. Loading rates were calculated between 20 and 80% of the period between footstrike and impact peak (vertical) or braking peak (anterior–posterior). This portion of the curve was chosen because it is the most linear portion of the initial loading part of the curve (Fig. 1). Average loading rate was calculated as the total change in force divided by the total change in time over this period. Instantaneous loading rate was the peak sample-to-sample loading rate occurring during this period. Tibial shock (peak positive acceleration (PPA)) was calculated after the average value and any linear trend in the acceleration signal were removed, as described by Shorten and Winslow (27). Peak positive acceleration was determined as the highest acceleration measurement during the stance phase. Knee flexion excursion (KEXC) was calculated as knee flexion range of motion from foot strike to peak knee flexion.

Joint torsional stiffness was calculated as the change in joint moment divided by the change in joint angle (7). It is recognized that these stiffness measures represent the sum of many individual stiffness measures and may, more accurately, be referred to as measures of quasistiffness (15). For the purposes of this report, however, the term stiffness will be used. Sagittal plane average knee joint stiffness (KSTIF) was determined from foot strike to peak knee

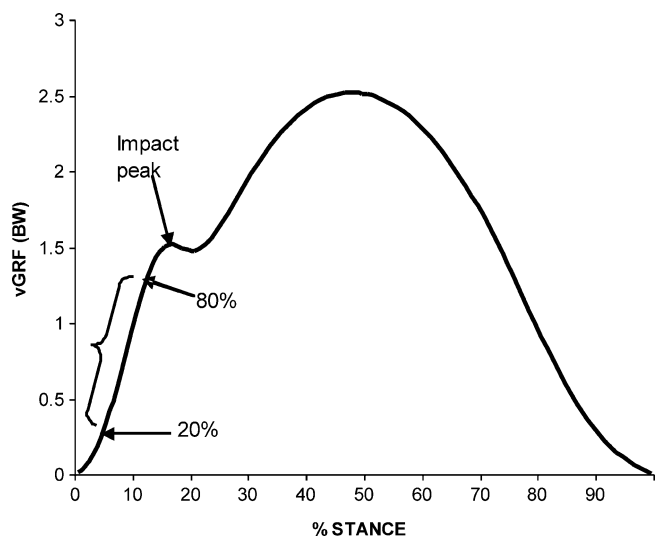


FIGURE 1—Instantaneous and average vertical loading rates calculated over the portion of the vertical ground reaction force curve between 20 and 80% of the time to impact peak. See text for full description.

flexion (i.e., the loading phase) during stance (Fig. 2). Sagittal plane average ankle joint stiffness (ASTIF) was determined from initial peak plantarflexion to peak dorsiflexion during stance (Fig. 2).

Strike index was calculated to confirm that all subjects were rearfoot strikers, having a strike index <33%, as defined by Cavanagh and Lafortune (4). Strike index is described by the point of intersection of a perpendicular drawn from the center point of pressure at footstrike and the long axis of the foot. This point of intersection is reported as a percentage of foot length from the heel.

All variables were determined for each of five trials per subject, averaged within the subject and then averaged across groups.

Structural measurements. Tibial x-ray studies were done for a subset of 33 subjects (18 TSF and 15 CTRL). The x-ray studies of both tibiae were taken from anterior and lateral views while standing with feet internally rotated 15° to account for the natural external rotation of the frontal plane of the tibia (22). A foot template was used to ensure consistency of foot placement between subjects. Tibial area moment of inertia (TIBAMI) was calculated from measurements made on the x-ray films, according to Milgrom et al. (22). As described by Milgrom et al. (22), the tibial cross-section was represented as an elliptical ring with an elliptical hole offset within it. Both the anterior-posterior and medial-lateral axes of rotation passed through the ring's centroid. Tibial varum was measured by an experienced physical therapist as the angle subtended by the bisection of the tibia in the frontal plane and a vertical reference.

Statistical analysis. Boxplots were used to identify outliers, defined as values >1.5 times the interquartile range away from the median. Identified outliers were removed from the data before statistical analysis of the differences between groups. A total of six data points fell outside this defined range and were removed as follows: two from the RTSF group for BALR, one from the CTRL group for ASTIF, one from each group for KSTIF, and one from the

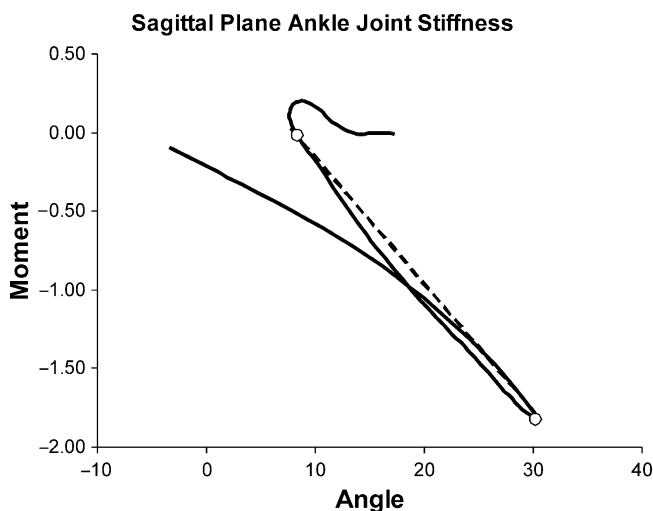


FIGURE 2—Calculation of average sagittal plane joint stiffness, depicting the ankle joint. See text for full description.

TABLE 1. Mean (SD) ground reaction force variables for retrospective tibial stress fracture (TSF) group and control (CTRL) group.

Ground Reaction Force	TSF	CTRL	Effect Size	P Value
IPEAK (BW)	1.84 (0.21)	1.70 (0.32)	0.51	0.057
VILR (BW·s ⁻¹)*	92.56 (24.74)	79.65 (18.81)	0.59	0.036
VALR (BW·s ⁻¹)*	78.97 (24.96)	66.31 (19.52)	0.56	0.041
BILR (BW·s ⁻¹)	20.35 (6.17)	19.29 (4.70)	0.19	0.272
BALR (BW·s ⁻¹)	8.54 (3.10)	8.37 (2.25)	0.07	0.420

* Significant at $P \leq 0.05$.

CTRL group for TIBAMI. One-tailed independent *t*-tests were used to test for significant differences between groups, based on the directional hypotheses stated previously. Bonferroni adjustments for multiple comparisons were not made as the hypotheses tested were developed *a priori* and, therefore, should be considered independent of each other (24). A binary logistic regression was carried out to determine whether PPA predicted group membership. The alpha level for all statistical tests was 0.05. We considered P values $0.05 < P \leq 0.10$ to be trends within the data. In addition, effect sizes were determined for all variables to aid in the interpretation of any trends found.

RESULTS

Instantaneous and average vertical loading rates were increased in the TSF group, compared with the control group (Table 1). A trend was also noted toward a higher impact peak ($P = 0.057$, moderate effect size = 0.51) in the TSF group. Loading rates during braking, however, were not different between the groups. The TSF group also showed a large increase in peak tibial shock compared with controls. A trend was also seen toward higher knee joint stiffness in the TSF group ($P = 0.054$, moderate effect size = 0.54), but ankle joint stiffness was not greater in the TSF group (Table 2). Knee flexion excursion also showed no differences between the two groups. The structural measure tibial varum also did not differ between the groups. The decrease in tibial area moment of inertia in the TSF group was small and not significant. A *post hoc* power analysis indicated that the study was underpowered to detect a 9% difference in TIBAMI, the magnitude of the difference between groups found by Milgrom et al. (22). The effect size in the present study was the same as that reported by Milgrom et al. (22).

The results of the binary logistic regression suggest that increased PPA is related to an increased likelihood of being in the TSF group. The model indicates that for every 1-g increase in PPA, the likelihood of having a history of TSF increases by a factor of 1.361 (95% confidence interval

TABLE 2. Mean (SD) joint excursion, stiffness, and structural variables for retrospective tibial stress fracture (TSF) group and control (CTRL) group.

	TSF	CTRL	Effect Size	P Value
KEXC	33.1 (5.0)	34.8 (5.2)	0.34	0.147
ASTIF ($\times 10^{-2}$)*	4.31 (0.59)	4.59 (0.61)	-0.46	†
KSTIF ($\times 10^{-2}$)	4.88 (0.88)	4.46 (0.68)	0.54	0.054
PPA*	7.70 (3.21)	5.81 (1.66)	0.74	0.014
TIBAMI	11312 (2883)	12224 (2387)	-0.34	0.174
TIBVAR	6 (2)	6 (2)	-0.36	0.128

* Significant at $P \leq 0.05$. † In opposite direction to hypothesized difference.

1.020–1.816, $P = 0.036$). According to the model chi-square statistic, the model is significant ($P = 0.020$). It also predicts group membership correctly in 70% of cases. The Nagelkerke R square value is 0.169, suggesting that 17% of the variance between the two groups is explained by PPA.

DISCUSSION

We investigated the biomechanical and structural differences between female distance runners with and without a history of TSF. Runners with a history of TSF exhibited greater instantaneous and average vertical loading rates, but no difference in loading rates during braking, compared with healthy controls. Differences in loading rates between these two groups have not been considered previously. Indications in our preliminary study (6) that both vertical and anterior–posterior loading rates are associated with a history of TSF were only partially supported by this more comprehensive study. The small net differences in loading rates during braking between groups (BILR 6%, BALR 2%) account for their lack of association with a history of stress fracture. In terms of peak ground reaction forces, runners who had sustained a previous TSF showed a small, nonsignificant (8% increase, $P = 0.057$) increase in the magnitude of the vertical impact peak compared with those who had never sustained a fracture. The moderate effect size (0.51) suggests, however, that impact peak may be an important factor in the cause of TSF. Although it is recognized that these are small increases, the cumulative effect of these slightly higher impacts in the TSF group may become important in injury development when repeated over thousands of foot strikes.

Based on our findings, TSF, which are fatigue fractures of the bone, appear to be most related to loading rates. Loading rate is one of the factors associated with its fatigue limit. The fatigue limit of a tissue is related to the type of load applied, its peak magnitude, loading rate, and the total dose. When comparing these two groups of runners, the type of load is similar (a combination of compression and bending), because both groups were rearfoot strikers. The total dose was assumed to be similar, because the groups were matched for mileage, although this method did not account for differences in absolute number of steps caused by the likely differences in stride length between subjects. The comparison of structure and alignment of the tibia also indicated that these were similar between the groups. Differences in load characteristics between the two groups, therefore, likely were reflected in the peak magnitude and loading rate. We hypothesized that both types of variables would be increased in the stress fracture group. Our results, combined with those of Crossley et al. (5) and Bennell et al. (2), however, suggest that the differences are in the vertical loading rate, rather than the impact peak or anterior–posterior loading rates during braking.

Peak tibial shock is another measure of the load applied to the lower extremity. Because a strong correlation has

been reported between vertical loading rates and tibial shock (17), we expected that shock would also be increased in the TSF group. As expected, we found a large increase in tibial shock in the stress fracture group, along with the increases in vertical loading rates. Additionally, tibial shock was found to predict a history of stress fracture in the binary logistic regression. Although it is a surrogate measure of bone loading, tibial shock actually provides a more direct estimate of the load acting on the tibia itself than ground reaction forces. Ground reaction forces represent the net forces acting on the center of mass of the whole body (27). Tibial shock, therefore, may be a more sensitive discriminator of runners at higher risk of TSF. While this needs to be confirmed with prospective studies, it may provide a means of screening for high-risk individuals. This measure is particularly amenable to mass screening because minimal preparation time is associated with its use, compared with a full kinematic and kinetic analysis of running gait.

The magnitudes of loading rates and peak tibial shock experienced during running are affected by the body's response to the applied load, as well as the magnitude of the load itself. The extreme example of Groucho running (20), in which the runner exaggerates knee flexion, provides a good illustration of this. When running with an extreme degree of knee flexion, the runner reduces the effective vertical stiffness of the lower extremity. The opposite is also true: running with reduced knee flexion increases the effective vertical stiffness of the lower extremity. We had expected to find significantly greater knee and ankle joint stiffness, accompanied by reduced knee joint excursion, in the TSF group. However, this was not supported by our results, which indicated only a trend toward increased knee stiffness in the TSF group ($P = 0.054$) for a 9% increase. The effect size, however, was moderate (0.54), indicating that stiffness may be an important factor. No difference was seen in excursion between the groups.

The decrease in TIBAMI in the TSF group was small, but showed the same small effect size (0.34) as found in 295 male infantry recruits who sustained a stress fracture during basic training (22). These recruits had a statistically smaller TIBAMI than those who did not fracture (22). In another study, however, several measures of tibial geometry showed no difference from normal in a group of 13 female runners with a history of TSF (2). It remains inconclusive whether decreases in TIBAMI are related to a history of TSF in female distance runners. Furthermore, tibial varum was no different between groups. This was unexpected, as Matheson (18) noted that varus malalignment was often present in male and female athletes with a history of stress fracture. We found that, in female distance runners, dynamic biomechanical characteristics of running gait associated with vertical loading show the greatest differences between groups.

The standardization of running speed and footwear reduces the number of extraneous variables contributing to differences between subjects during the laboratory-based comparison of running mechanics. During the follow-up

period, however, footwear and running speed were not monitored. This is a limitation of the study because the running mechanics recorded in the laboratory may differ slightly from those that the subject experiences during normal running. Differences in footwear and running speed may affect the magnitude of lower extremity loading experienced. Furthermore, the conclusions drawn from this study should be interpreted with caution because the study was retrospective and cross-sectional. Prospective studies of runners who sustain a TSF are needed to determine cause and effect with respect to loading rates and fracture occurrence.

In conclusion, based on the results of this study, a history of TSF in female runners is associated with increases in several dynamic loading-related variables:

instantaneous and average vertical loading rate and peak tibial shock. A trend toward higher knee stiffness and impact peak, indicated by a moderate effect size for history of TSF, but not statistically significant differences, was also found. No significant differences were found in the structural measures of tibial area moment of inertia and tibial varum angle in this group of runners with a history of TSF compared with a healthy control group. The magnitude of peak tibial shock predicted group membership successfully in 70% of cases.

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Gait Retraining in Runners

Irene S. Davis, PT, PhD, FACSM

Running is a popular fitness activity with over 15 million Americans engaging in the sport. Due to its aerobic nature, it has tremendous cardiovascular benefits. However, it is a sport that also involves repetitive loading. For example, a typical runner will strike the ground approximately 1000 times per mile with each foot. Therefore, even minor malalignments and/or abnormal movement patterns can accumulate into an overuse injury. In fact, it has been reported that 50% to 87% of runners will sustain an injury over a one-year period. With 15 million runners in the United States, the number of running related injuries is in the millions. This is associated with substantial medical costs. In addition, cessation of running as a fitness activity can impact one's overall fitness level. The Healthy People 2010 initiative has linked one's fitness level with longevity and productivity.

The etiology of running injuries is multifactorial and each runner has their own threshold for injury. This threshold is dependent on their structure, their mechanics, and their dosage. These factors are interactive and determine how close one functions to their injury threshold. For example, one runner may have poor structural alignment resulting in abnormal mechanics, but only run 10 miles per week. They may continue to run uninjured until they decide to increase their dosage and train for a half-marathon. This increased dosage, in concert with their poor structure and mechanics, may now place them at or above their injury threshold. On the other hand, another runner may have excellent alignment and mechanics, but run ultramarathons, placing him or her at their injury threshold. Therefore, these factors can interact in numerous ways.

While some aspects of structure, such as flexibility, can be altered, basic anatomy is considered relatively unchangeable. Of the 3 factors described, dosage is clearly the most modifiable. However, runners become accustomed to certain running dosage, typically measured by miles run per week. They are reluctant to significantly reduce this mileage as they

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The etiology of running injuries is multifactorial and each runner has their own threshold for injury.
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feel they lose the conditioning effects of the exercise. This leaves mechanics which are also modifiable. It is generally believed that mechanics play a significant role in the development of running related injuries. Therefore, altering these mechanics should help to reduce injury risk. In addition, if one has already sustained an injury thought to be related to their mechanics, the risk for reinjury is high unless these mechanics are altered.

The idea of altering one's movement patterns is not new. Therapists are trained to alter abnormal patterns in their patients to reduce injury risk. They do this in their daily practice. For example, they often train their patients to change the manner in which they lift objects in order to reduce spinal loads. However, gait is often thought of as an automatic skill that some believe is driven by central pattern generators. Therefore, the notion that these automatic actions can be changed through conscious thought is often questioned. However, if we believe that movement patterns can be changed, then there is some hope that gait patterns also can be changed to help reduce injury risk.

There is emerging evidence in the literature that kinematic adaptations are indeed possible through neuromuscular reeducation. A recent study by Hewett et al¹ reported lower extremity mechanics during landing from a jump could be significantly altered through a plyometric training program. The program was designed to teach athletes to land softer and with better lower extremity alignment. Reductions in ground reaction forces and knee moments were noted. In a follow-up study, these same authors reported a significant reduction in serious knee injuries among female athletes

who had undergone this training program.²

Gait may be more difficult to alter given its repetitive and automatic nature. However, there have been numerous reports in the literature documenting the success of using some type of real time feedback training to alter walking gait. The majority of these report on patients with neurologic involvement, such as adults who have sustained a stroke or children with cerebral palsy. The earliest forms of feedback were limb load monitors placed within the shoe of a patient.^{3,5} The aim of this type of feedback was to produce an equal load distribution between lower extremities during gait. Electromyography is one of the most widely used forms of feedback reported in the literature. Reports of improvements in gait symmetry in terms of spatio-temporal parameters and joint motion patterns have been reported.^{6,10} Feedback on joint angles has been provided through the use of electrogoniometers for patients with genu recurvatum.¹¹⁻¹³ An overwhelming majority of these studies have reported successful results.

Reports of real-time feedback training are beginning to emerge in the orthopaedic literature. White et al¹⁴ first demonstrated that providing real time visual feedback from an instrumented treadmill could be used to train healthy individuals to exhibit asymmetrical limping strategies. Using the same protocol, they then provided real time feedback, 3 times a week for 8 weeks, to patients who had undergone a hip replacement.¹⁵ They reported a significant improvement in symmetry of reaction forces at weight acceptance. In a related study, Dingwell¹⁶ used an instrumented treadmill to improve the gait of a group of unilateral, trans-tibial amputees. Prior to the training, asymmetries in the measured parameters were 4.6 times greater in the amputee group compared to the control group. These asymmetries were significantly reduced following the training.

However, studies involving feedback during running are sparse. Messier et al¹⁷ provided verbal and visual feedback to a group of female novice runners over a 5

week, 3 sessions per week, running program. Prior to each training session, runners were shown a videotape of their running and were instructed on the features of their gait that they were to try to modify. These were subject-specific mechanics and included characteristics such as excessive vertical oscillation, over-striding, excessive trunk lean, and excessive arm rotation. This group of runners significantly altered the desired kinematic gait variables compared to a control group who received no feedback prior to their training sessions. While this study did not involve the use of real-time feedback, it demonstrates that runners are able to alter their mechanics with training.

Prior to making changes in one's movement patterns, it is important to identify those patterns that are to be related to injury. This can only be done through prospective investigations. We have been engaged in prospective studies to identify biomechanical factors associated with stress fractures, as well as those associated with anterior knee pain. Both of these injuries are among the top 5 most common injuries that runners sustain.¹⁸ In addition, females are at least twice as likely to sustain these injuries compared to their male counterparts. Therefore, our prospective studies were focused on female runners between the ages of 18 and 45 years. In order to eliminate the influence of fitness in our study, all subjects had to be running a minimum of 20 miles per week. Following the instrumented gait analysis, runners are followed monthly for a period of 2 years. Running mileage, as well as any injuries that are sustained are reported. Our preliminary data suggests that female runners who go on to develop a stress fracture exhibit significantly higher peak tibial shock, as well as increased vertical loading rates compared to a group of uninjured age and mileage matched group. Runners who go on to develop anterior knee pain exhibit increased hip adduction and internal rotation. These findings provide the rationale needed to alter these mechanics in runners.

We began our realtime feedback training with the use of a treadmill and a mirror. We have since further developed our realtime feedback to include realtime accelerometry and realtime motion analysis feedback. The following prelimi-

nary and case studies will hopefully demonstrate how realtime feedback can be used to retrain abnormal gait patterns in runners.

STUDY 1

Gait Retraining in a Runner with Plantar Fasciitis

A 40-year-old female runner with right plantar fasciitis served as the subject for this study. She had discontinued running as a result of her pain. Prior to her injury, she had been running an average of 15 to 20 miles per week. She had been treated unsuccessfully with foot orthotic devices and was seeking additional advice. A visual analysis of the patient's running revealed the following (Figure 1a): the right hip was in excessive internal rotation and the knee in genu valgum throughout the support phase. In addition, excessive midfoot pronation was observed. Weakness of the right hip abductors and external rotators was noted (4/5 on a manual muscle test), as well as excessive hip internal rotation range of motion (0-70°). The left side exhibited normal hip strength and range of motion.

An instrumented gait analysis was performed to quantify the gait deviations that were noted visually. The frontal and transverse plane motions of the hip and knee are shown in Figure 2 (left panel) and compared to that of a group of healthy runners. Hip adduction and internal rotation and knee abduction and external rotation were found to be greater in the injured runner. It was hypothesized that the plantar fasciitis this runner was experiencing was related to the internally rotated hip and medially deviated position of the knee, placing

greater stress on the arch of the foot. The subject agreed to undergo an 8-week training program to address these gait mechanics. Visual feedback was provided as the patient ran on a treadmill in front of a full-length mirror. The patient was instructed verbally to "keep your knees apart" to address the hip adduction. In addition, she was asked to "keep your patella pointed forward" to address the internal rotation of the femur. She ran for 10 minutes and gradually progressed to 32 minutes by the end of the 8-week session. She was seen 3 times a week for the first 3 weeks, 2 times a week for the next 3 weeks, and once a week for the last 2 weeks. The mirror and verbal feedback were progressively removed. She reported soreness in the external rotators and abductors of her right hip during the initial training, which resolved within 2 weeks. She also reported a progressive reduction in the effort required to maintain the aligned posture of her right lower extremity. The subject underwent another instrumented gait analysis to assess any changes that occurred as a result of the training.

Following the gait re-training program, there was a significant reduction in hip internal rotation, hip adduction, and knee abduction and increase in knee internal rotation (as a result of the decreased femoral internal rotation) (Figure 1b & Figure 2 right panel). The runner returned for a 6 month follow-up gait analysis. She was running 30 minutes, 3 to 4 times per week without pain. The analysis revealed that hip external rotation and abduction were maintained, but knee frontal plane patterns showed a shift towards pretraining levels (Figure 2 right panel).

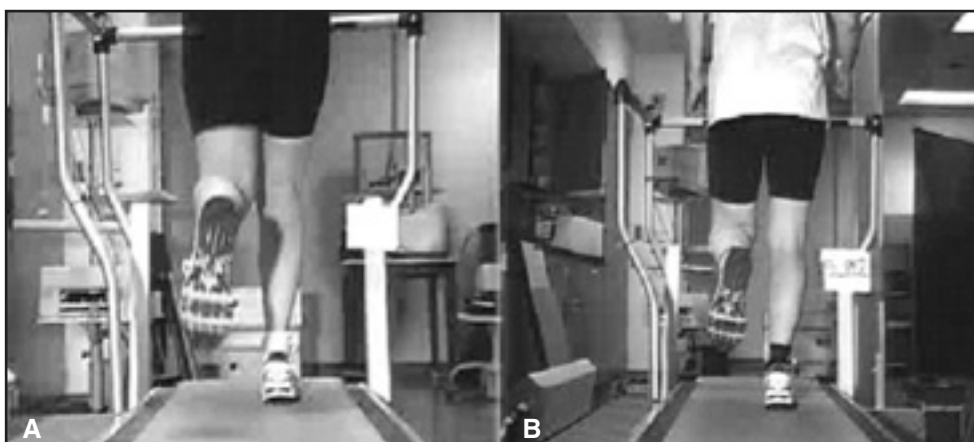


Figure 1. (a) Pretraining gait. Note the genu valgum and hip adduction position. (b) Post-training gait. Note the reduced genu valgum and hip adduction.

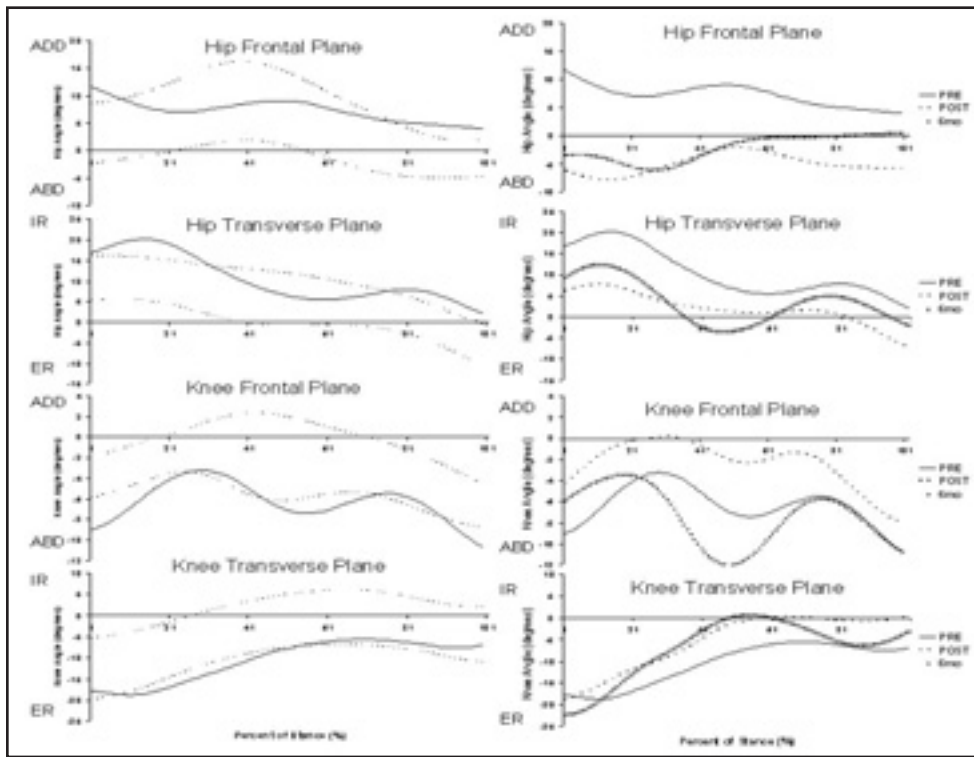


Figure 2. Hip and knee frontal and transverse plane pretraining angular position curves compared to the $\pm 1SD$ of the normative database (left) and compared to post-training and 6 month follow-up (right).

Results of this study clearly suggest that the patterns of running gait can be modified. These modifications led to a resolution of the patient's symptoms. However, she reported that the symptoms would return when she became fatigued and reverted to her old pattern. This further supports the hypothesis that the abnormal mechanics were causing the symptoms. Finally, this case study demonstrates the ability of the runner to maintain these new patterns over a 6-month period.

STUDY 2 Gait Retraining in a Runner with Patellofemoral Pain

The subject was a 46-year-old female runner who had been running for 15 years and had been averaging 15 miles per week. She had recently been training for a marathon when she developed left anterior knee pain, prompting her to seek physical therapy advice. Upon evaluation, it was noted that this runner exhibited weakness of the hip abductors and external rotators (4/5 on a manual muscle test). Upon performing a lateral stepdown, she exhibited excessive knee valgum, hip adduction, and femoral internal rotation. A visual gait analysis during running revealed increased hip adduction and internal rotation, knee valgus,

and rearfoot pronation during stance (Figure 3a). An instrumented gait analysis revealed excessive hip internal rotation. It was hypothesized that this runner's patellofemoral pain was due to an excessively internally rotated femur and would be resolved if her gait mechanics could be altered so that she exhibited greater hip external rotation during stance. Thus, this runner was placed in a gait retraining program consisting of visits twice a week for 10 weeks.

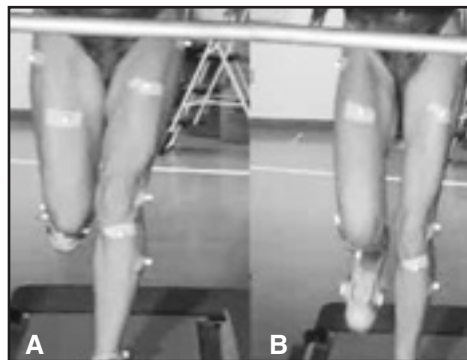


Figure 3. Pre (left) and post (right) training Hip IR. Note the reduction following gait retraining.

A real time motion analysis system was used for this retraining. Retroreflective markers were placed on the left leg. The motion was recorded in real-time with 6 cameras sampling at 120 Hz. The Vicon

370 (Oxford Metrics, UK) 120 Hz 6-camera motion analysis system was used to collect bilateral lower extremity 3D joint kinematic data while the subject ran on a treadmill for 30 minutes (Figure 4). The processed 3D kinematic data collected by the Vicon DataStation were transferred to the Vicon Real-Time Engine which output marker and segment positions and rotations. This information was then on-line transferred to Polygon software where lower extremity segment and marker position data were displayed on a monitor for the subject to observe. Data were only presented during the stance phase of gait by selecting triggers based on heel and toe marker kinematic data. The patient was asked to alter her gait mechanics by shifting the chosen angular curve in the appropriate direction to provide more normal alignment. A real-time display of her hip internal rotation angle was provided as the subject ran on the treadmill at her self-selected pace (Figure 4). The subject was asked to lower her hip internal rotation curve (without altering her foot placement angle).



Figure 4. Subject running on the treadmill with retro-reflective markers placed on her pelvis, thighs, shanks, and feet. A video monitor (right) was provided for real-time feedback.

Over the 10-week training period, the runner was able to reduce her amount of hip internal rotation as she ran. This subject also experienced muscle soreness in her hip abductors and external rotators following training. Again, this soreness resolved over the first 2 weeks of gait retraining. By the 5th week of training, the visual feedback was periodically withdrawn. The patellofemoral pain this runner had experienced was resolved and she was able to reduce the amount of hip internal rotation throughout stance (Figure 3b and 5).

This study demonstrates the effective use of the integrated real-time video feed-

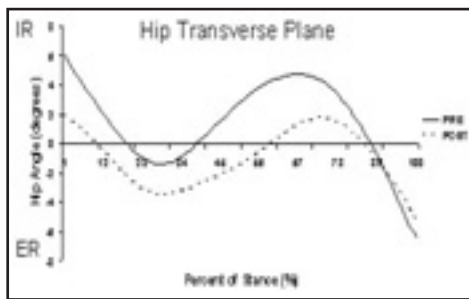


Figure 5. Pre and post-training Hip IR – note the decrease after gait retraining.

back system. The Vicon motion analysis company has just released their first version of their realtime analog feedback system. This will allow us to provide kinetic feedback on variables such as tibial shock, as well as vertical impact peaks measured on the instrumented treadmill.

STUDY 3

Preliminary Study of the Effect of Realtime Feedback During Running on Tibial Shock

The purpose of this preliminary study was to determine whether a runner could reduce their tibial shock while running on a treadmill and receiving a simple real-time feedback display of their shock levels. Four healthy recreational runners (age 25-35 yrs) volunteered to participate in this pilot study. Subjects were all rearfoot strikers without any current lower extremity injuries or conditions that might influence their running mechanics. An accelerometer was attached to their right distal tibia in an anteromedial position. Each subject ran on the treadmill at their own comfortable speed (range 6.0 - 7.0 mph) for 5 minutes. Data were then collected for 5 seconds to establish the subject's baseline values for tibial shock. A monitor, placed in front of the treadmill, then provided a real time visual display of their shock pattern as the subject ran. A horizontal line was placed on the video display at a position that was approximately 50% of each individual's peak shock value. Subjects were instructed to reduce the size of the peaks to below the horizontal target on the screen. They were simply told to try to "run more softly." They were allowed to practice this new pattern with the continuous visual feedback from the tibial shock curve for a period of 5 minutes, after which a second 5-second trial was again collected. The mean peak positive acceleration (tibial shock) was determined over 5 foot

strikes for each trial. A one-tailed paired t-test was used to determine whether tibial shock was reduced following the real time feedback. Based on the preliminary nature of this study, an alpha of $P < 0.10$ was used to determine significance.

Following the 5 minutes of feedback, each participant was able to reduce their mean tibial shock. The group mean reduction was 30%, which was significant at the $P = 0.08$ level (Table 1).

This preliminary study demonstrates that runners are able to reduce the loading of their lower extremity by an average of 30% with a very brief training session. Only one of these subjects exhibited a baseline tibial shock value in the high risk range (> 8.89 g's, which was 1.0 standard deviations above the mean of a healthy reference population of runners). There was a considerably lower range of post retraining values for tibial shock compared to the baseline values. This may indicate that there is a floor effect in the potential for those with a normal or low shock value to reduce their shock further. It is notable that the subject with the highest baseline shock produced the greatest reduction. This suggests that we may see large reductions in our proposed study when using a population of high risk runners.

STUDY 4

Preliminary Study of the Short-Term Retention of Gait Changes Developed during Realtime Feedback to Reduce Tibial Shock

The purpose of this preliminary study was to assess the effect of realtime feedback of tibial shock on both tibial shock and ground reaction forces. Therefore, the study was conducted at the University of Massachusetts where an instrumented treadmill is available. Three healthy recreational runners (age 23-28 yrs) volunteered to participate in this pilot.

An accelerometer was attached to their right distal tibia in an anteromedial position. Subjects ran on a force-measur-

ing instrumented treadmill to monitor concurrent changes in ground reaction force. Each subject ran on the treadmill at their own comfortable speed (range 5.4 - 5.9 mph) for 5 minutes. Data were then collected for 5 seconds to establish the subject's baseline values for tibial shock and ground reaction force. A monitor, placed in front of the treadmill, then provided a real time visual display of their shock pattern as the subject ran. A horizontal line was placed on the video display at a position that was approximately 50% of each individual's peak shock value. Subjects were instructed to reduce the size of the peaks to below the horizontal target on the screen. They were simply told to try to "run more softly." They were allowed to practice this new pattern with the continuous visual feedback from the tibial shock curve for a period of 10 minutes, after which a second 5-second trial was collected. This period of training was followed by a second 10-minute period during which no feedback was provided. The subjects were instructed to continue running in the new way that they had been practicing. No further verbal feedback was given. At the end of this period, a further 5 second trial was collected. The subject then cooled down for 5 minutes. The mean peak positive acceleration (tibial shock) was determined over 5 foot strikes for each trial. The variables considered were peak tibial shock, average vertical loading rate and impact peak. All of these have been associated with tibial stress fracture retrospectively in our previous studies.

Following the 10 minutes of feedback, each participant was able to make a sizeable reduction in their mean tibial shock (Table 2). Average loading rate and impact peak were also reduced.

Following the 10-minute period without feedback, the participants were able to maintain their reduction in tibial shock. Average loading rate and impact peak also remained reduced, compared to baseline values (Table 3).

Table 1. Baseline and Post-training Peak Tibial Shock Values (* $P = 0.08$)

Subject	Normal (g)	Post Training (g)	Reduction (%)
1	4.51 ± 0.89	3.92 ± 0.67	13.22
2	3.71 ± 0.73	3.44 ± 0.43	7.19
3	4.77 ± 0.26	2.64 ± 1.67	44.54
4	9.41 ± 0.48	4.05 ± 1.27	57.00
Mean	5.60 ± 2.58	3.51 ± 0.63*	30.49

Table 2. Baseline and Post-training Peak Tibial Shock Values

Variable	Baseline	Post-training	Reduction (%)
Tibial shock (g)	7.29 ± 1.25	3.83 ± 0.37	47.51
Ave load rate (BW/s)	28.39 ± 3.72	20.05 ± 1.14	29.37
Impact peak (BW)	1.50 ± 0.12	1.11 ± 0.16	25.71

Table 3. Baseline and Maintenance Period Peak Tibial Shock Values

Variable	Baseline	Maintenance	Reduction (%)
Tibial shock (g)	7.29 ± 1.25	3.77 ± 0.17	49.33
Ave load rate (BW/s)	28.39 ± 3.72	21.35 ± 4.39	24.82
Impact peak (BW)	1.50 ± 0.12	1.13 ± 0.25	24.52

This preliminary study demonstrates that runners are able to reduce the loading of their lower extremity by an average of more than 25% with a very brief training session, with a particularly large decrease in tibial shock, the variable used to provide feedback. All of these subjects had baseline values of tibial shock within the normal range and were still able to make large reductions following a brief training period. This effect was maintained in the short-term when feedback was removed, indicating the potential for runners to learn a modified running gait.

STUDY 5

Gait Retraining Case Study of Patient with High Tibial Shock

This subject was a 20-year-old female collegiate runner with a history of multiple overuse injuries of her left lower extremity. Evaluation of her gait mechanics (session 1) revealed high loading variables (especially tibial shock) with the left being greater. This subject lived 2 hours from the university and could not undergo a prolonged course of retraining. However, she was provided verbal instruction in softening her landing while running on a treadmill. She was given the opportunity to practice this technique for approximately 20 minutes during treadmill running. She returned in one year and asked to be reassessed. At that visit, we tested her while running over-ground again (session 2a), provided her with 30 minutes of realtime feedback on her tibial shock during treadmill running and then tested her again (session 2b).

Table 4 and Figure 6 demonstrate the reduction in the magnitude of the loading variables from her baseline to her 1 yr follow-up. In addition, her loading was further reduced with additional feedback training that day. There was a reduction

in all variables with the exception of the impact force, all other variables decreased. This subject now reports being able to run competitively and remain injury-free.

FUTURE DIRECTIONS

While these preliminary and case studies have demonstrated that gait patterns can be changed, there is much work to be done in this area. Research is needed to determine the optimal gait retraining protocols. This includes determining the feedback variables that provide the most effective results. In addition, work needs to be done in optimizing the feedback training schedules. Finally, we need more follow-up studies to determine the permanence of these

gait related changes and their influence on future injury incidence. These are the investigations that we are currently engaged in. It is hoped that by further understanding the etiology of running-related injuries, we can better direct interventions towards minimizing them. In this way, we can help runners remain healthy throughout their lifetime.

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Table 4. Comparison of Loading Variables Across Sessions

Variable	Tibial shock (g)	Fz Impact (bw)	Inst. Load Rate (bw/s)	Av Load Rate (bw/s)
Session 1	11.13	1.8	140.2	128.4
Session 2a	9.5	2.0	93.6	63.2
Session 2b	8.43	1.9	85.9	52.8

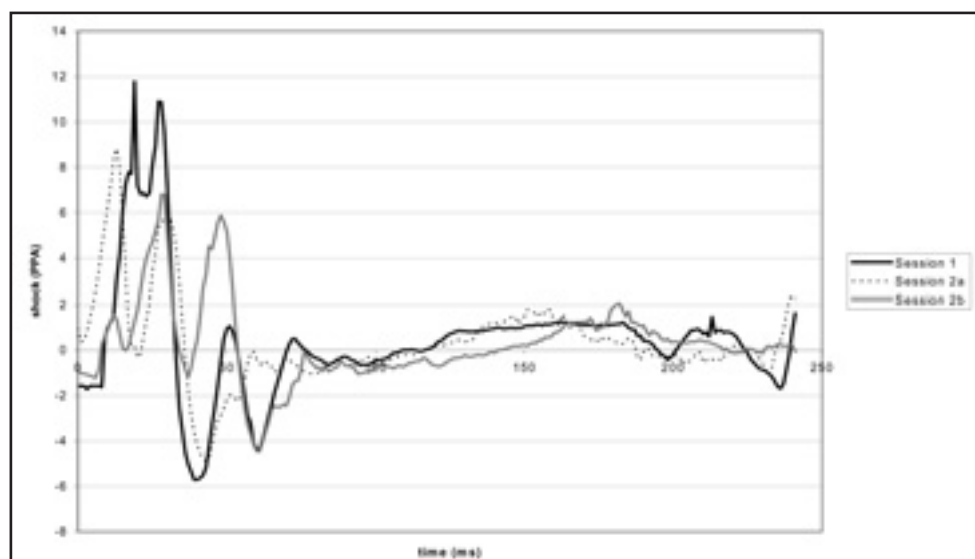


Figure 6. Progressive reduction in peak tibial shock from baseline (session 1) to 1 year follow-up (session 2a) to post-training at the 1 year follow-up.

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Free moment as a predictor of tibial stress fracture in distance runners

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Abstract

Stress fractures are a common and serious overuse injury in runners, particularly female runners. They may be related to loading characteristics of the lower extremity during running stance. Some tibial stress fractures (TSFs) are spiral in nature and, therefore, may be related to torque. Free moment (FM) is a measure of torque about a vertical axis at the interface with the shoe and ground. Increases in FM variables may be related to a history of TSF in runners. The purpose of this cross-sectional study was to investigate differences in FM between female distance runners with and without a history of TSF and, additionally, to investigate the relationship between absolute FM and the occurrence of TSF. A group of 25 currently uninjured female distance runners with a history of TSF (28 ± 10 years, 46 ± 15 km week⁻¹) and an age- and mileage-matched control group of 25 healthy runners with no previous lower extremity fractures (26 ± 9 years, 46 ± 19 km week⁻¹) participated in this study. Ground reaction forces and foot placement on the force platform were recorded during running at 3.7 m s^{-1} ($\pm 5\%$). Peak adduction, braking peak and absolute peak FM and impulse were compared between groups using one-tailed *t*-tests. The predictive value of absolute peak FM was investigated via a binary logistic regression. All variables, except impulse, were significantly greater in runners with a history of TSF. Absolute peak FM had a significant predictive relationship with history of TSF. There is a significant relationship between higher values for FM variables and a history of TSF.

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Keywords: Ground reaction forces; Running; Female

1. Introduction

Overuse injuries occur frequently in runners, with incidence rates as high as 85% being reported in the literature (Bovens et al., 1989). The most serious overuse injury in terms of recovery time is a stress fracture. Lower extremity stress fractures typically require 6–8 weeks rest from running to allow the bone to heal. Stress fractures are one of the five most common injuries in the running population, accounting for between 6% and 14% of all injuries sustained by runners (James et al., 1978; McBryde, 1985). The most commonly injured bone is the tibia, with tibial stress fractures (TSFs)

accounting for between 35% and 49% of all stress fractures in runners (Matheson et al., 1987; McBryde, 1985). There is also a gender bias in the occurrence of stress fractures, with women reported consistently as being at twice the risk of sustaining stress fracture than men (Arendt et al., 2003). Reasons for this gender bias are unclear: it may be partly related to lower bone density or differences in bone geometry in females compared to males, although existing studies are inconclusive (Beck et al., 2000; Bennell et al., 2004).

Recent studies of TSFs have suggested that their occurrence may be related to higher loading of the lower extremity (Milner et al., 2005). Additionally, there is evidence that some TSFs are spiral fractures (Spector et al., 1983). This suggests that, in addition to vertical and shear forces, torques may be involved in the development of a TSF. However, the frequency of

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occurrence of spiral TSF is unknown, since they are usually classified according to their anatomical location on the tibia (Spector et al., 1983). Furthermore, Ekenman et al. (1998) reported that the tibia is exposed to a combination of bending, shearing and torsion simultaneously during activities such as running. The free moment (FM) is the torque about a vertical axis due to friction between the foot and the ground during stance (Holden and Cavanagh, 1991). While FM has been linked to pronation (Holden and Cavanagh, 1991), its potential role in running injuries has not been widely investigated. Although FM is not a direct measure of the torque acting on the tibia, higher FM is likely to contribute to higher torque. As an indicator of the torque about a vertical axis experienced at the point of contact between the foot and the ground, FM is worthy of further investigation in relation to stress fracture.

Preliminary work in our laboratory showed a higher peak adduction FM (resistance to toeing out) and trends towards greater FM at peak braking force and net angular impulse in 13 runners with a history of TSF, compared to runners with no previous lower extremity bony injuries (Milner et al., 2004). FM at peak braking force may be important if both shear and torque are high at the same time. These trends suggest that there might be significant differences in FM variables between the groups if a larger subject pool were analyzed. Furthermore, the preliminary study did not consider the absolute magnitude of peak FM. Since this study indicated that some runners may have an abduction bias in FM (more than 50% stance with abduction FM), considering only their peak adduction FM would not indicate the greatest torque acting on their lower extremity. Therefore, an absolute measure (peak regardless of direction) may better represent the magnitude of the torque acting on the lower extremity.

The purpose of this cross-sectional study was to investigate differences in FM between female distance runners with and without a history of TSF and, additionally, to investigate the relationship between absolute FM and the occurrence of TSF. We hypothesized that maximum adduction FM (ADDFM), FM at peak braking force (FMBRAK), net angular impulse (IMP) and absolute peak FM ($|FM|$) would be greater in runners with a history of TSF compared to those who had never sustained a lower extremity bony injury. In addition, we hypothesized that $|FM|$ would be predictive of group membership.

2. Methods

2.1. Subjects

All subjects gave their written informed consent prior to participation in the study. All procedures were

approved by the Institution's Human Subjects Review Board prior to the commencement of this study. Participants were recruited from local races, running clubs and teams. Subjects were excluded if they were currently injured, had abnormal menses (missed more than three consecutive monthly periods in the previous 12 months), were pregnant or suspected they were pregnant. A group of 25 currently uninjured female distance runners with a history of TSF (28 ± 10 years, 46 ± 15 km week⁻¹) and an age- and mileage-matched control group of 25 healthy runners with no previous lower extremity fractures (26 ± 9 years, 46 ± 19 km week⁻¹: CTRL) participated in this study. The TSF group was an average of 48 months post-injury (range 3–120 months). The majority (23/25) had one previous TSF; one subject had two previous TSFs and another had four previous TSFs. It was not known how many subjects had spiral TSFs. A priori power calculations were based on data from a preliminary study conducted in our laboratory (Milner et al., 2004). Based on an α level of 0.05, β of 0.20 and effect sizes of 0.78 for FMBRAK and 0.48 for IMP, 24 subjects were needed to detect a twofold difference between groups (Lieber, 1990). ADDFM was significantly different between groups in the preliminary study. On entry into the study, the TSF group had reported a previous TSF, which had been confirmed by a medical professional and diagnostic imaging tests (bone scan, MRI or X-ray). All subjects were rearfoot strikers, having a strike index of ≤ 0.33 (Cavanagh and LaFortune, 1980). This was to ensure that they had a similar loading pattern, since there are differences in ground reaction force patterns between rearfoot, midfoot and forefoot strikers.

2.2. Experimental protocol

Ground reaction force data were collected at 960 Hz using a strain-gaged force platform (Bertec Corporation, Columbus, OH) as the subjects ran overground along a 23 m runway at 3.7 m s⁻¹ ($\pm 5\%$). Running speed was monitored via two photocells placed 2.88 m apart and linked to a timer. Footwear was standardized with all subjects wearing the same make and model of a commercially available neutral shoe. Data were collected for a single stance phase per trial, as the subject contacted the force platform located in the center of the runway. Five acceptable trials were collected. Trials in which the subject appeared to change their gait or target the force platform were discarded. Prior to data collection, subjects performed practice trials to ensure that they would achieve the required speed and correct foot placement on the force platform without modifying their gait. Holden and Cavanagh (1991) noted differences between FM on the right and left sides of an individual. Therefore, foot contact on the force platform was on the involved side in the TSF group, to capture

the appropriate FM data. Since neither side had a previous TSF in the CTRL group, there was no reason to prefer one side over the other; therefore, foot contact was made on the right side.

Kinematic data were collected, using a six camera motion capture system (Vicon, Oxford, UK) sampling at 120 Hz, for the calculation of strike index (Cavanagh and LaFortune, 1980). Retroreflective tracking markers were placed proximally and distally on the vertical bisection of the heel counter of the shoe and on the lateral part of the heel. In addition to marker position data collection during the running trials, a standing trial was collected with an additional anatomical marker placed on the tip of the toe box. This marker was used to determine the position of the long axis of the foot and its position and orientation in the global coordinate system during stance.

Data were processed using custom LabView programs (National Instruments Corporation, Austin, TX). FM is the torque about a vertical axis due to friction between foot and ground during stance. Following the sign convention of Holden and Cavanagh (1991), positive FM acts to resist toeing out (ADDFM) and negative FM acts to resist toeing in (ABDFM) (Fig. 1). To preserve this sign convention, the FM calculation that follows was negated for the right foot. FM was calculated from the components of moment and force output from the force platform. FM is one of two components of the moment, M_z , acting about a vertical axis at the center of the force platform. The second component is the moment due to the resultant shear force acting through the center of pressure. Detailed examples of the relationship between FM and the moment about a vertical axis at the center of the force

platform were provided by Holden and Cavanagh (1991). The equation describing the contributions of these two components to the vertical moment was used to derive FM from force platform output (Bertec Corporation, 2003). All force platform channels were baseline adjusted to a zero offset when unloaded prior to calculating FM.

$$FM = M_z - (CP_x \cdot F_y) + (CP_y \cdot F_x),$$

$$CP_x = -M_y/F_z \text{ and } CP_y = M_x/F_z,$$

where M_z is the moment about the z -axis, CP_x the x -coordinate of center of pressure, F_y the ground reaction force in y -direction, CP_y the y -coordinate of center of pressure, F_x the ground reaction force in x -direction, M_y the moment about y -axis, F_z the ground reaction force in z -direction and M_x the moment about x -axis. Positive y -axis was in the direction of progression, positive z -axis was vertically downwards and positive x -axis was to the left when facing the direction of progression, following the right-hand rule. FM was normalized by dividing by body weight and height, making the reported FM dimensionless (and IMP in seconds). This reduces the effects of differences in weight and height between subjects on the magnitude of FM and facilitates meaningful comparisons between subjects.

Each variable was averaged over five trials per subject. ADDFM was the maximum adduction value of FM during stance; FMBRAK was the FM at peak braking force during stance; Impulse was the net area under the FM curve during stance; $|FM|$ was the maximum absolute value of FM during stance.

Strike index was calculated as the position of the center of pressure at foot strike, relative to the long axis of the foot at foot flat. In the current study, it was determined by the point of intersection of a perpendicular from the center of pressure to the long axis of the foot. This position of this point along the long axis is calculated as a proportion of the overall length of the long axis away from the heel. Rearfoot striking is defined as a strike index ≤ 0.33 (Cavanagh and LaFortune, 1980). Strike index was determined using custom Visual Basic programs (Microsoft Corp) and Visual 3D software (C-Motion, Rockville, MD). All subjects were rearfoot strikers, with mean values for strike index of 0.08 ± 0.05 for the TSF group, and 0.09 ± 0.05 for the CTRL group.

Independent t -tests were used to test for significant differences between groups. Since we were only interested in whether the values of FM variables would be greater than normal in the TSF group, one-tailed tests were used. Lower values for FM variables in the TSF group were interpreted in the same way as no difference between groups.

A binary logistic regression was carried out to determine whether $|FM|$ predicted group membership.

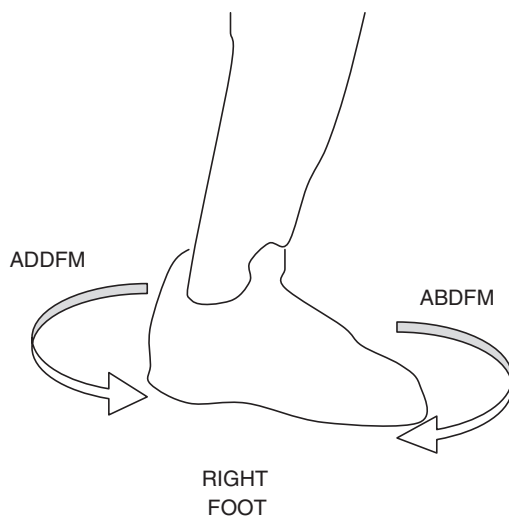


Fig. 1. Representation of adduction free moment resisting toe out and abduction free moment resisting toe in of the foot during contact with the ground.

The alpha level for all statistical tests was 0.05. In addition, effect sizes were determined for all variables, to aid the interpretation of any differences found. Ensemble average curves are also presented, both for the TSF and CTRL groups as a whole, and for subdivisions of subjects with adduction and abduction FM bias. FM bias was determined from the percent of stance with adduction FM for each subject. Subjects with adduction FM for more than 50% of stance are designated as having an adduction FM bias and others as having a abduction FM bias. This subdivision of subjects was conducted to further explore whether $|FM|$ was more appropriate than ADDFM as a representative FM variable.

3. Results

All variables indicated that FM was greater in the TSF group (Table 1, Fig. 2). While the magnitude of FM was significantly greater in the TSF group for both ADDFM and FMBRAK, the highest values in both groups were

Table 1
Average normalized free moment variables in female runners with (TSF) and without (CTRL) a history of tibial stress fracture

	ADDFM	FMBRAK	IMP (s)	$ FM $
TSF	7.7±4.7	4.6±5.7	4.5±9.9	9.3±4.3
CTRL	4.7±2.5	1.6±3.7	1.6±5.5	5.9±2.1
Effect size	0.80	0.62	0.36	0.99
<i>P</i>	0.004	0.017	0.105	<0.001

All variables are $\times 10^{-3}$, except IMP which is $\times 10^{-4}$.

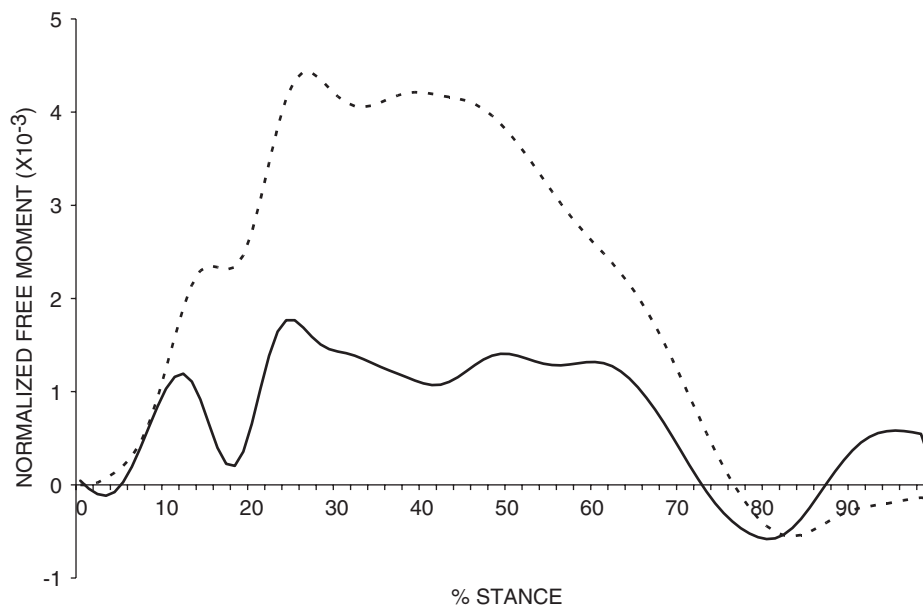


Fig. 2. Average normalized free moment during stance in female runners with (TSF; dashed line) and without (CTRL; solid line) a history of TSF.

found for $|FM|$. $|FM|$ also had a larger effect size (0.99) than ADDFM (0.80). The higher value of $|FM|$, compared to ADDFM, indicates that in some runners ABDFM (resistance to toeing in) is greater in magnitude than ADDFM (resistance to toeing out). Mean ABDFM was smaller than both ADDFM and $|FM|$ and not different between the groups (TSF: 2.9 ± 4.3 ; CTRL: 2.9 ± 2.7), confirming that ABDFM was high in only a few subjects. There was no difference in IMP between the groups. The group average curves provide an indication of the general pattern of FM during stance (Fig. 2), but as can be seen from the large spread indicated by the standard deviation in Table 1, the shape of the FM curve was quite variable between subjects. This is partly due to some runners having an abduction FM bias (7 in TSF and 9 in CTRL), illustrated in Figs. 3 and 4.

Results of the binary logistic regression suggested that higher $|FM|$ was related to an increased likelihood of being in the TSF group. The model indicated that for every 1.0×10^{-3} increment in $|FM|$, the likelihood of having a history of TSF increased by a factor of 1.365 (95% confidence interval 1.099–1.695, $p = 0.005$). According to the model χ^2 statistic, the model is significant ($p = 0.001$). It also predicted group membership correctly in 66% of the cases. The Nagelkerke R^2 value was 0.274, suggesting that 27% of the variance between the two groups is explained by $|FM|$.

4. Discussion

We investigated the differences in FM between female distance runners with a history of TSF and those who

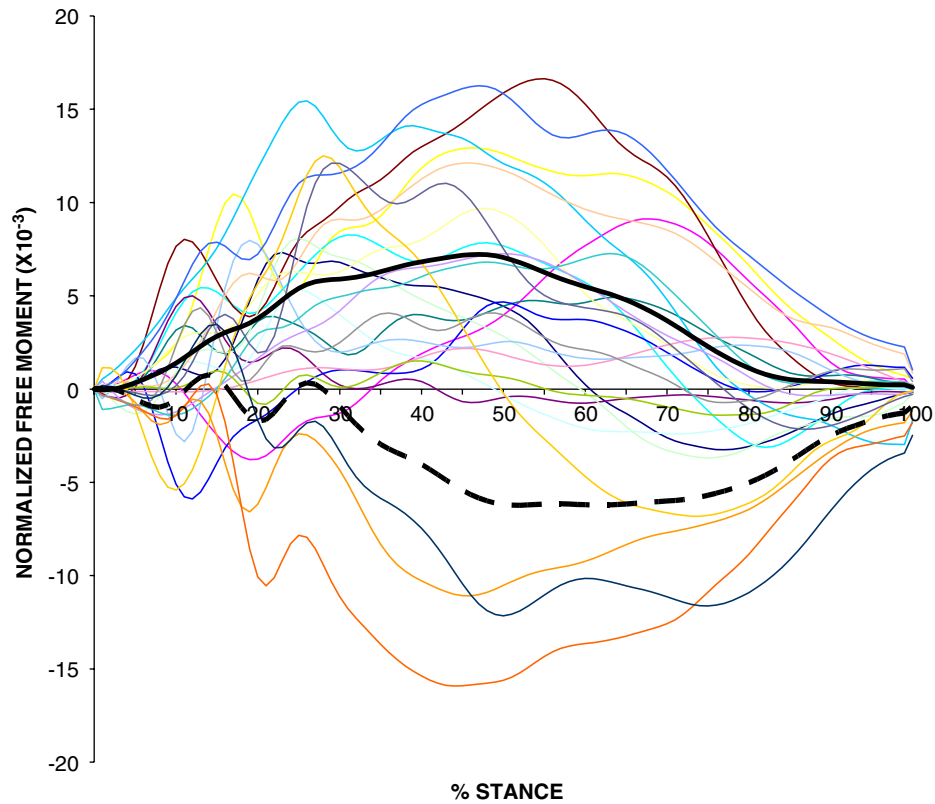


Fig. 3. Average normalized free moment during stance in female runners with a history of TSF. Heavy lines represent average values for subgroups with adduction ($n = 19$; solid) and abduction ($n = 6$; dashed) free moment bias.

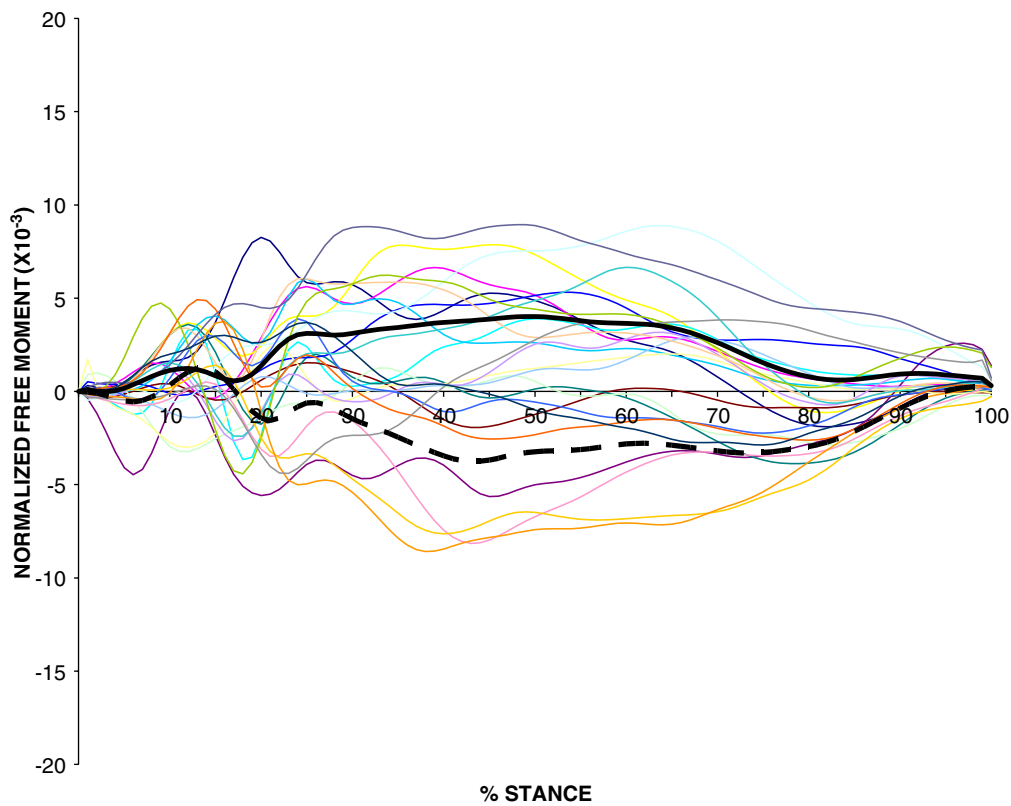


Fig. 4. Average normalized free moment during stance in female runners without a history of TSF. Heavy lines represent average values for subgroups with adduction ($n = 14$; solid) and abduction ($n = 9$; dashed) free moment bias.

had never sustained a lower extremity bony injury. Three of the four FM variables compared between groups were greater in the TSF group. The largest effect size was found with |FM| (although effect sizes of both |FM| and ADDFM were large). Higher values of |FM| compared to ADDFM were found in both groups. Since ABDFM was smaller than ADDFM in both groups, this indicates that in some runners, ABDFM was greater in magnitude than ADDFM. We also observed that some runners have an abduction bias in their FM curve. Therefore, ADDFM does not reflect the highest torque experienced by these subjects. However, |FM| provides an indication of the peak magnitude of the torque acting on the lower extremity in all runners. The higher FM values found in the TSF group suggest that higher than normal torque may be associated with TSF. Since differences in |FM| are larger than differences in ADDFM between groups, the magnitude of the torque may be more important than its direction in relation to stress fracture injury.

The lack of significant difference between groups in IMP, despite a threefold higher value in the TSF group compared to the CTRL group, may be explained by the large spread within the data, particularly in the TSF group. Some runners had a large positive FM, while others had a large negative FM for most of the stance phase, and in others FM was small in magnitude for most of the stance phase. As can be seen in the figures, there was a wide variation in the pattern of free moment during the stance phase of running both within and between groups.

Furthermore, as is typical in ensemble curves, the peaks are attenuated relative to the individual curves due to differences in the timing of peaks between subjects. Group average curves provide an indication of the general pattern of FM during stance, but as can be seen from the large spread indicated by the standard deviation in Table 1, this was quite variable between subjects. Due to the bias of some runners in both groups towards abduction FM, there is a large spread in the groups, particularly the TSF group. While there was no distinct pattern in the relative occurrence of adduction and abduction FM bias between the two groups, inter-individual differences were clear. Consequently, the mean ensemble average curves would be of limited interpretive value in making comparisons with individuals, rather than between groups. In addition, since some subjects have an abduction bias and others an adduction bias, the mean curve lies somewhere in between these and does not represent either well. When the groups were subdivided by FM bias, the resulting mean curves provided a more representative average curve.

The values for FM in the control group were somewhat similar to those reported in the literature (Heise and Martin, 2001; Holden and Cavanagh, 1991). There was some variation between these two studies,

with the former reporting ADDFM 4.9×10^{-3} and the latter ADDFM of 9.7×10^{-3} . Reported values for IMP were similar at 5.0×10^{-4} and 4.7×10^{-4} , respectively. ADDFM for the control group in the present study was similar to that reported by Heise and Martin (2001), but IMP in the control group was lower than reported by these two groups. There are several methodological differences between each of these two studies and the present study. Both previous studies used male runners, whereas the present study used female runners. Gender differences in various biomechanical characteristics during running have been reported previously (Ferber et al, 2003). Furthermore, the runners tested by Holden and Cavanagh (1991) ran at a faster speed (4.5 m s^{-1}) than either of the later studies (Heise and Martin, 2001 3.35 m s^{-1} ; present study 3.7 m s^{-1}). Speed has also been shown previously to affect the mechanics of running (Nilsson et al., 1985) and may, therefore, affect transmission of the torque to the lower extremity and the magnitude of the FM variables. The present study provides information about the characteristics of FM in normal female runners, as well as those with a history of TSF.

Further support for the importance of |FM| in TSF was provided by the binary logistic regression. The results of the binary logistic regression indicate that |FM| is a good predictor of a history of TSF. This suggests that |FM| may be a useful tool in screening for runners at risk of TSF. However, while a predictive relationship with previous TSF has been shown, it is beyond the scope of this cross-sectional retrospective study to determine whether |FM| is also higher in runners before they sustain a TSF. Further prospective studies are needed to determine the utility of |FM| in predicting future TSF in runners.

In conclusion, peak adduction FM, FM at peak braking force, and absolute peak FM were significantly higher in runners with a history of TSF compared to a control group with no previous lower extremity bony injury. This suggests an association between higher FM and history of TSF in female distance runners. The magnitude of absolute peak FM successfully predicted a history of TSF in this group in 66% of cases.

Acknowledgments

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