Modeling of Kinetic Risk Factors for Exercise Related Lower Leg Pain in Collegiate Female Track and Field Athletes

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APPROVALS

We certify that we have read this dissertation and that, in our opinion, it is satisfactory in scope and quality as a dissertation for the degree of Doctor of Philosophy in Education.

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"Time and change will surely show, how firm they friendship…"

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ABSTRACT

Exercise related lower leg pain is a common problem among the physically active, occurring more often in women than men. The exact mechanism underlying the most common causes of this condition in physically active individuals is controversial. Exercise related lower leg pain (ERLLP) is a broad diagnosis representing the shared clinical manifestations of medial tibial stress syndrome, tibial stress fractures (TSF) and chronic exertional compartment syndrome. Previous ERLLP research has focused on identifying associated risk factors and is limited by retrospective research designs, using different methods of injury modeling that fail to consider dynamic free moment variables or changes due to exercise. Free moment (FM) has been associated with a history of TSF but has not been examined relative to ERLLP. Therefore, the purpose of this study was to examine kinetic risk factors associated with both previous or subsequent ERLLP in female, NCAA Division I intercollegiate track and field athletes using two different injury models. Subjects were 31 female athletes from the same NCAA division I track and field team. Kinetic analysis was performed prior to and following an exhaustive bout of treadmill exercise. Injury history was collected prior to testing and subjects were subsequently tracked through the three month competitive season for the development of ERLLP resulting in activity modification. Injury modeling using logistic regression was based on pre-exercise kinetic measures and fatigue-induced changes in kinetic variables. Injury probability was modeled using two separate injury classifications (retrospective vs. prospective) and two separate injury models (one leg per subject vs. two). Significant models, which included FM variables, were found for retrospective injury from both pre-exercise and fatigue-induced gait kinetics. No significant models for predicting prospective injury were found. While retrospective models were similarly effective using either injury model, these models were not effective for predicting the development of ERLLP. Consequently, while either injury model may be used effectively in predicting previous ERLLP in female track athletes, care should be taken when attempting to predict injury development based on retrospective modeling.

PART I

INTRODUCTION

Exercise related lower leg pain (ERLLP) is a common condition among physically active individuals, reported to affect 12-15% [4, 35] of high-school runners, 18% of physically active female college students [43], 24-35% of individuals involved in military training [24, 47] and is more common in women than men [4, 8, 43, 47]. Several distinct pathologies may be included under this broad diagnosis including medial tibial stress syndrome (MTSS), tibial stress fractures (TSF) and chronic exertional compartment syndrome (CECS) [43, 45]; all of the aforementioned pathologies appear to arise from discrete mechanisms [2, 22, 23, 29]. Research has shown that MTSS exists as a distinctly different pathology from chronic exertional compartment syndrome [33]; however the relationship between MTSS and TSF is more controversial though it is believed that these two conditions share a similar mechanism [2, 22, 25]. Considerable debate exists regarding the precise mechanism for MTSS and TSF [2, 6, 23, 29] and clinical differentiation may be difficult without advanced diagnostic techniques [1, 7, 22, 23]. Consequently, the term ERLLP has evolved as a broad diagnosis that demonstrates the shared clinical manifestations of these two conditions and resulting activity time loss among those affected [7, 43].

Current ERLLP research has centered on the identification of developmental risk factors and has provided insight into the kinematic and kinetic variables associated with its component pathologies [3, 15, 29, 32, 35, 38, 43, 47]. The primary limitation in this line of research involves the use of retrospective designs thus limiting the ability to understand the causative factors since it is not possible to determine whether observed differences are the cause or the effect of the injury [3, 10, 18, 27, 32, 38-41].

Prospective research designs in ERLLP have been limited by the variables chosen for measurement in these studies which have generally included static foot postures, such as navicular drop or standing rearfoot alignment [4, 35, 37, 47]. Results of previous studies have indicated that static foot measurements are poor predictors of functional mechanics; only the analysis of dynamic kinetic variables can account for the dynamic forces experienced during running [4, 9, 26]. Dynamic prospective ERLLP studies are limited and do not account for training volume or method of measuring kinetic running variables [14, 43, 45]. Interestingly, some of the prospectively identified risk factors have been in agreement with previous retrospective studies [27, 33, 39] while others have not [18].

Previous ERLLP research has also been limited by inconsistent modeling of the pathologies studied. These studies used the uninjured limb of a subject with a single injured limb as part of the control group [43, 45]; it may be argued that this model is inappropriate due to the possible effect of the injured leg on the uninjured leg. To address this possibility, other studies have utilized a single injured or uninjured limb from each subject to assess differences [31, 36]. It is unclear whether these two models would produce similar results within a given subject or sample.

Additional limitations of previous ERLLP research involve the difficulty in measuring kinematic foot characteristics commonly associated with various lower extremity overuse injuries, such as pronation [20, 27, 40, 47], and their association with differences in ground reaction forces between injury status groups. Kinematic differences between subjects may not translate into ground reaction force differences necessitating direct measurement of kinetic variables. [17, 31, 36]. One kinetic variable that has been shown sensitive to changes in pronation but has received little attention in published literature is the free moment of ground reaction (FM) [17]. The FM is a force couple around the vertical axis of a horizontal running surface resulting due to rotational shear forces between the foot and the ground during stance [17]. Adduction FM is the rotational ground reaction force (GRF) resisting foot abduction during stance, a component of pronation, conversely abduction FM is the rotational GRF resisting foot adduction[17, 31]. Adduction FM and absolute FM (maximal FM whether adduction FM or abduction FM) have been found to be significantly greater in subjects with a history of TSF [31, 36]. However, it is unclear whether kinetic measures including FM serve as significant predictors of injury in ERLLP despite the relationship between increased FM measures and previous TSF.

Finally, previous ERLLP research does not account for risk factors owing to fatigue. Decreases in eccentric muscle control due to fatigue have been associated with increased tibial strain during loading representing an increased risk for the development of TSF [29]. Significant differences in the degree of kinetic changes due to acute fatigue [14] have also been observed in individuals with and without histories of lower extremity injuries. The well established changes in gait dynamics following prolonged exercise [13, 14] may magnify the dynamic kinetic characteristics responsible for the development of ERLLP. To our knowledge, no studies have examined the effect of acute fatigue on kinetic gait characteristics, either retrospectively or prospectively, associated with the development of ERLLP.

Therefore, based on the limitations of the aforementioned studies and the increased incidence of ERLLP in women and the physically active, this study was designed to examine kinetic risk factors associated with both previous and subsequent ERLLP in female, NCAA Division I intercollegiate track and field athletes using two different injury models. The first injury model used both legs from each subject for analysis while the other used only a single injured or healthy leg from each subject. The following research hypotheses were developed:

1. Predictive models for retrospective ERLLP will be similarly effective for predicting prospective ERLLP injuries in subjects.
2. Predictive models for ERLLP using a both-legs-per-subject model (BL) will be similarly effective as a one-leg-per-subject model (OL) of injury in subjects.
3. Free moment of ground force reaction measures will be significantly associated with ERLLP in subjects.
4. Changes in kinetic variables due to acute fatigue will be significantly associated with ERLLP in subjects.

METHOD

Subjects

Subjects were 31 trained female college athletes from the same NCAA Division I intercollegiate track and field team. Prior to study enrollment, subjects completed institutional human subjects committee approved informed consent forms (appendix A). All subjects had been cleared for physical activity through a pre-participation physical examination conducted by a team physician. Descriptive data means and standard deviations for subjects are presented in table 1.

Table 1. Subject descriptive data (mean ± SD)

N	31		
Age (years)	20.0	±	1.6
Height (cm)	166.7	±	7.0
Weight (kg)	60.4	±	7.0
BMI	21.7	±	2.2
Body Composition (%)*	17.8	±	3.4

*Body density calculated using Jackson and Pollock sum of seven sites equation. Body composition calculated using Siri body density equation.

Instrumentation and Protocol

Lower leg injury history and training history data were collected using the ERLLP injury history form (appendix B). The injury history assessment was designed to classify previous incidences of ERLLP based on the definition developed by the Council of Europe which describes an injury as a reduction in the amount or level of sports activity[43]. Instructions for the ERLLP injury history assessment specifically instructed participants not to consider diagnosed cases of CECS, acute injuries or injuries to the knee, ankle or calf / Achilles tendon. Subjects who presented with lower extremity injury deemed to effect performance or activity participation during data collection were excluded from study participation.

All data were collected by the same Board of Certification Certified Athletic Trainer (BOCATC). Anthropometric data, including height, weight and skinfold thickness were collected for all subjects. Height was determined using a stadometer and weight determined using a Detecto Certifier Scale. Skinfolds were obtained in duplicate using Lange calipers at seven sites as described by Jackson and Pollock [19]. Kinetic data were collected using a force platform at 480 Hz (Model LG6-4, Advanced Medical Technology, Inc., Newton, MA) embedded flush with the running surface along a 20 meter runway. All data were smoothed with a fourth order recursive Butterworth filter at 20 Hz and processed using Peak Motus v. 9.0 software (Peak Performance Technologies, Inc, Denver, CO). During testing, subjects wore spandex running shorts, sports bra and their regular running shoes.

Following a subject directed warm-up of jogging and stretching, subjects completed familiarization practice trials to ensure consistent running speed of $4.0\ m \cdot s^{-1} \pm$ 10% and landing with each foot in the center of each force platform during data collection trials. Adherence to the required running speed was determined using Speedtrap II (Brower Timing Systems, Draper, UT) infrared sensors placed six meters apart, at each end of the force plate mounting pit.

Kinetic assessment was based on three successful trials for each foot. Previous authors have suggested that based on the high reliability between trials, analysis and interpretation of gait data based on mean values of only a few trials is sufficient [11, 43, 44]. A successful trial was based on the following criteria: 1) subjects completed the pass through the field at the required running velocity and 2) the subjects' foot landed on the force platform with no visible alteration of the running stride [3, 10, 43, 45]. All variables were calculated as the mean of three successful trials for each foot.

Kinetic data were collected prior to and following an exhaustive bout of treadmill exercise involving a graded maximal exercise tests (GXT) specifically designed to induce lower leg fatigue. Standard instructions were given prior to the GXT as to the importance of maximal effort by the participant. The treadmill protocol began with completion of the Modified Åstrand Protocol (MAP) [16] to determine VO_{2max}. Metabolic data were collected during the MAP using standard indirect calorimetry procedures via open-circuit spirometry. Heart rate and Rating of Perceived Exertion [5] were collected at the end of each testing stage. Running speed for the GXT was determined by the subject as a comfortable running speed between five and eight mph. Subjects were blinded to the speed of the treadmill throughout the testing procedure. The MAP was terminated based on the point of volitional exhaustion for each subject. Upon completion of the MAP, subjects were given a three minute active recovery at 1% grade on the treadmill at a self-selected walking pace. During the three minute active recovery stage, the metabolic data collection mouthpiece was removed. Following the active recovery stage, the mouthpiece was replaced and treadmill speed increased to a velocity predicted to elicit

80% VO_{2max} at 1% grade as determined by ACSM equations for estimating oxygen consumption [21]. Metabolic data collected during the first three minutes of this stage were used to determine if further velocity adjustment were necessary to elicit an oxygen consumption of 80 ± 5% VO_{2max}. Following verification of 80 ± 5% VO_{2max} intensity at 1% grade, the mouthpiece and headgear were removed. Subjects continued running at the prescribed speed with grade increased 2.5% every three minutes until volitional exhaustion. Following completion of the treadmill protocol, subjects were allowed to walk at a self-selected pace for two minutes then sit and recover for up to five minutes. Following this short recovery period, gait kinetics were reassessed as described previously.

During the 3 month competitive indoor and outdoor track seasons following pre-season testing, subjects were monitored and assessed for the development of ERLLP by members of the research team, who are BOCATCs. Monitoring included administration of the "Bi-weekly ERLLP Injury History Questionnaire" (appendix C) and daily care as provided by the team's BOCATC.

Data Analysis

Subjects were separated into injury and control group designations using two different injury models: 1) both legs from each subject were included in the analysis (BL) and placed in either the injured or uninjured grouping, and 2) only one leg from each subject was included in the analysis (OL). In the OL model, subjects with no injury or bilateral injury, the right leg was used; otherwise, only the single injured leg was used for a given subject [31].

Based on the data collected from the injury history questionnaire, subjects were classified into previous ERLLP injury (RI – retrospective injury) and no previous history of ERLLP injury (NRI – no retrospective injury) groups for the retrospective portion of the analysis. The same characterization used in the retrospective injury classification, was used to classify lower leg injury development during the study (PI – prospective injury) and no lower leg injury development (NPI – no prospective injury) groups, for prospective analysis. Subjects who developed non-ERLLP lower extremity injuries that prevented completion of the competitive season and/or study procedures were excluded from the prospective analysis. Separate retrospective and prospective analyses of risk factors related to the development of ERRLP were completed for BL and OL.

All statistical analyses were completed using SAS (version 9.1) with an alpha level set at $p<0.05$. Paired t-tests were used to assess differences in biomechanical variables between left and right foot trials. Separate logistic regression analyses were performed to assess the relationship between each set of kinetic variables (1. pre-exercise and 2. fatigue-induced changes resulting from acute exercise exposure) and each injury status classification (1. retrospective and 2. prospective) for each injury model (1. BL and 2. OL). The following eight kinetic measures were used as dependent variables during analysis: FMBRAK (peak FM at maximum braking during stance), APGRF (peak braking ground reaction force normalized for subjects' body weight), ADDFM (peak adduction free moment), ABSFM (absolute peak free moment whether, adduction or abduction), IMP (adduction angular impulse defined by the area under the FM curve during stance), VGRF (peak vertical ground reaction force normalized for body weight), LR (loading rate of VGRF normalized for body weight) and BR% (percentage of stance involved in braking phase). All FM variables were normalized for subjects' body weight and height creating dimensionless FM variables and IMP expressed in seconds as described by Milner et al., allowing for comparisons between subjects [31]. Significant logistic regression models were subsequently applied to the alternate injury status (retrospective vs. prospective) and injury model (BL vs. OL). Differences in risk factors identified and the efficacy of prediction models between retrospective and prospective analyses and between injury models were compared based on the previous statistical procedures.

RESULTS

A total of 31 subjects completed the initial kinetic gait analysis. One subject was diagnosed with CECS during the competitive season and was not considered in any analyses. A second subject was not cleared for GXT and consequently did not complete the exercise protocol or the second gait analysis, eliminating the ability to calculate changes in kinetic variables due to fatigue for this subject. Thus, pre-exercise data from 30 subjects were used for analysis of kinetic gait characteristics relative to retrospective and prospective injury; data from 29 subjects were used for analysis of fatigue-induced changes in kinetic gait characteristics relative to retrospective and prospective injury. No significant differences were found between the left and right foot for any of the kinetic dependent variables. Therefore, left and right foot data were considered together for subsequent analyses.

Subjects reported a mean sport-specific training volume of approximately 15 hours per week at the time of testing (mean response 3.5 ± 0.6 on ERLLP Injury History Questionnaire – see appendix B). During the competitive season, subjects reported a mean sport-specific training volume of approximately 10 hours per week (mean 3.0 ± 1.2 response on Bi-weekly ERLLP Injury History Questionnaire – see appendix C). Subjects represented a range of track and field event participation. Ten subjects identified themselves primarily as distance runners, eight as participating primarily in jumping events, six as sprinters, four as middle distance runners, two as heptathletes/pentathletes and one as a thrower. Differences in kinetic gait characteristics and injury prevalence based on event participation were not assessed in the present study as most subjects regularly participated in more than one event.

Retrospective Injury

Thirteen subjects (42%) reported previous ERLLP serious enough to require a reduction in the amount or level of sports activity. Seven subjects reported ERLLP history bilaterally and six unilaterally, for a total of 20 RI legs and 40 NRI legs.

Modeling of Gait Kinetics Using BL

Four pre-exercise kinetic variables were identified as significant contributors ($p<0.05$) to the logistic regression models in two separate combinations of three variables each. Table 2 presents regression coefficients for each significant logistic model. In both cases, reduced models of main effects were found to explain injury history as adequately as a full model which included interactions (model one: χ^2 difference = 1.14, df = 4; model two: χ^2 difference = 7.73, df = 4).

In model one, the regression coefficients for ABSFM and FMBRAK were negative, indicating a decreased magnitude associated with greater probability of ERLLP history, while the coefficient for IMP was positive. The model indicated that for every 1.0×10^{-3} increment increase in ABSFM or FMBRAK, risk of previous ERLLP injury decreased by 58% and 26%, respectively. For every 1.0×10^{-4} increase in IMP, risk of previous ERLLP increased by 2.58 times. When applied to OL, only ABSFM and IMP remained significant. However, parameter estimates were identical in sign to BL;

magnitude of parameter estimates and odds ratios for all three variables were similar to BL.

The percent of concordant, discordant and tied observation pairs were also similar for model one using either BL or OL. Within the logistic regression model, a pair was concordant if the response variable with the lower ordered response variable (NRI) had a lower predicted event probability than the higher ordered value response (RI). A pair was discordant if the lower ordered response variable observation had a higher predicted event probability than the observation with the higher ordered value of the response. A pair that was neither concordant nor discordant was categorized as tied. Percentages for each category were based on all pairs of observations with different values of the response variable (NRI vs. RI). Percent concordant, discordant and tied pairs for all retrospective models comparing BL and OL are presented in table 3.

In model two, the regression coefficients for ABSFM and BR% were negative while IMP was positive. This combination of variables was also significant when applied to OL (table 2) with similar regression coefficients and odds ratios (table 4). No significant model for predicting ERLLP history from fatigue-induced kinetic changes using BL was revealed in the logistic regression procedure. Comparisons of parameter estimates and odds ratios for BL and OL in all significant retrospective models are presented in table 4. Mean (±SD) values for significant variables in each model are presented in table 5.

Table 2. Logistic regression data for predicting retrospective ERLLP in female, NCAA Division I track and field athletes

Pre-exercise gait kinetics using BL

	Parameter Estimate	Wald Chi-square	Pr>Chi Sq
Model 1			
Intercept	1.57	2.28	0.131
ABSFM	-857.50	9.68	0.002
IMP	9458.70	9.05	0.003
FMBRAK	-301.90	4.16	0.041
Model 2			
Intercept	14.82	5.24	0.022
ABSFM	-768.50	8.66	0.003
IMP	5896.70	7.50	0.006
BR%	-25.88	4.50	0.034

Pre-exercise gait kinetics using OL

	Parameter Estimate	Wald Chi-square	Pr>Chi Sq
Intercept	28.17	4.70	0.030
ABSFM	-1106.30	5.66	0.017
IMP	7557.40	4.46	0.036
BR%	-49.15	4.21	0.040

Fatigue-induced changes in gait kinetics using OL

	Parameter Estimate	Wald Chi-square	Pr>Chi Sq
Intercept	-0.49	1.16	0.282
APGRF	-0.06	3.96	0.047
IMP	791.00	3.99	0.046

ABSFM: Absolute peak free moment; IMP: Adduction angular impulse; FMBRAK: Free moment at peak braking force; BR%: Percent of stance involved in braking; APGRF: Peak braking ground reaction force; BL: injury model using both legs per subject; OL: injury model using one leg per subject

Modeling of Gait Kinetics Using OL

One significant combination of three kinetic variables was indicated for predicting retrospective injury from pre-exercise gait data using the OL model (table 2). As was the case for the significant retrospective BL models, the reduced model of only main effects was found to explain injury history as adequately as a full model which included interactions (χ^2 difference = 5.28, df = 4). In this model, the IMP regression coefficient was positive, indicating a greater magnitude associated with greater probability of ERLLP history, while ABSFM and BR% were negative. This combination of variables was identical to those found to be significant in one of the two significant models using BL with similar regression coefficients and odds ratios (table 4) as well as a similar percentage of concordant, discordant and tied pairs (table 3).

One significant model of two kinetic variables was found for predicting retrospective injury from fatigue-induced changes in kinetic gait using OL (table 2). In this model, the regression coefficient for APGRF was negative while IMP was positive. When applied to BL, neither of the variables in this model was significant; parameter estimates and odds ratio for IMP were similar between OL and BL though APGRF was not. Parameter estimates and odds ratios for these variables applied to BL are presented in table 4 and percentages of concordant, discordant and tied pairs for this model are presented in table 3. Mean (±SD) values for significant variables for each of these OL models are presented in table 5.

Table 3. Percent concordant, discordant and tied pairs in logistic models for predicting ERLLP in female, NCAA Division I track and field athletes

		Pairs	Percent Concordant	Percent Discordant	Percent Tied
Pre-exercise gait kinetics					
Model 1 - ABSFM, IMP, FMBRAK					
BL	Retrospective*	800	79.1	20.9	0.0
	Prospective	611	65.0	34.2	0.8
OL	Retrospective	221	80.5	19.0	0.5
	Prospective†	n/a	n/a	n/a	n/a
Model 2 - ABSFM, IMP, BR%					
BL	Retrospective*	800	84.5	15.5	0.0
	Prospective	611	54.2	45.0	0.8
OL	Retrospective*	221	86.4	13.1	0.5
	Prospective	176	61.9	36.9	1.1
Fatigue-induced changes in gait kinetics					
Model - APGRF, IMP					
OL	Retrospective*	208	76.9	23.1	0.0
	Prospective	168	56.0	42.9	1.2

ABSFM: Absolute peak free moment; IMP: Adduction angular impulse; FMBRAK: Free moment at peak braking force; BR%: Percent of stance involved in braking; APGRF: Peak braking ground reaction force; BL: injury model using both legs per subject; OL: injury model using one leg per subject

*Indicates significant logistic model ($p<0.05$)

†Prospective data were not assessed using OL for this model since retrospective model was not significant

Table 4. Comparison of regression coefficients and odds ratios between retrospective injury models for predicting ERLLP in female, NCAA Division I track and field athletes

	Retrospective			
	BL		**OL**	
Pre-exercise gait kinetics				
Model 1	**Parameter Estimate**	**Odds Ratio**	**Parameter Estimate**	**Odds Ratio**
ABSFM	-857.50*	0.42‡	-1066.60†	0.34‡
IMP	9458.70*	2.58§	10527.90†	2.87§
FMBRAK	-301.90*	0.74‡	-282.20	0.75‡
Model 2				
ABSFM	-768.50*	0.46‡	-1106.30*	0.33‡
IMP	5896.70*	1.80§	7557.40*	2.13§
BR%	-25.88*	0.77¶	-49.15*	0.61¶
Fatigue-induced changes in gait kinetics				
APGRF	-1.20	0.30	-0.06*	0.94
IMP	2264.20	1.25§	791.00*	1.08§

ABSFM: Absolute peak free moment; IMP: Adduction angular impulse; FMBRAK: Free moment at peak braking force; BR%: Percent of stance involved in braking; APGRF: Peak braking ground reaction force; BL: injury model using both legs per subject; OL: injury model using one leg per subject

* Significant variable as part of overall significant logistic model ($p<0.05$)

† Significant variable ($p<0.05$) within overall non-significant logistic model

‡ $e^{\text{parameter}(0.001-0.000)}$

§ $e^{\text{parameter}(0.0001-0.0000)}$

¶ $e^{\text{parameter}(0.01-0.00)}$

Table 5. Kinetic variables included in significant logistic regression models (mean ± SD) for predicting ERLLP in female, NCAA Division I track and field athletes

Retrospective injury using BL			
ABSFM*	5.52	±	1.78
IMP (s)†	2.93	±	2.19
FMBRAK*	1.92	±	3.64
BR%	0.51	±	0.03
Retrospective injury using OL			
ABSFM*	5.30	±	1.92
IMP (s)†	3.08	±	2.12
BR%	0.51	±	0.03
Delta APGRF (n·m)‡	-0.03	±	0.30
Delta IMP (s)†‡	0.43	±	1.44

ABSFM: Absolute peak free moment; IMP: Adduction angular impulse; FMBRAK: Free moment at peak braking force; BR%: Percent of stance involved in braking; APGRF: Peak braking ground reaction force; BL: injury model using both legs per subject; OL: injury model using one leg per subject

*Values are x10^{-3}

†Values are x10^{-4}

‡Delta kinetic variables represent fatigue-induced changes (post - pre)

Prospective Injury

Eight subjects (26%) developed ERLLP during the competitive season significant enough to require a reduction in the amount or intensity of sport participation. Five subjects developed ERLLP bilaterally and three unilaterally for a total of 13 PI legs and 47 NPI legs. Fifty percent of subjects who developed ERLLP (n=4) reported a previous injury on the ERLLP Injury History Questionnaire. No combination of either pre-exercise kinetic variables or fatigue-induced changes in kinetic variables was significant in predicting the development of ERLLP in our subjects. When each of the significant models from the retrospective analyses was applied to the prospective injury classification, none of the variables considered were significant contributors; odds ratios were dissimilar in magnitude, parameter estimates were dissimilar in magnitude and sign (table 6) and percentage of concordant pairs was markedly decreased in prospective modeling (table 3).

Table 6. Comparison of regression coefficients and odds ratios between prospective injury models for predicting ERLLP in female, NCAA Division I track and field athletes

	Prospective			
	BL		**OL**	
Pre-exercise gait kinetics				
Model 1	**Parameter Estimate**	**Odds Ratio**	**Parameter Estimate**	**Odds Ratio**
ABSFM	-155.80	0.86‡		
IMP	-2514.50	0.78§		
FMBRAK	330.90	1.39‡		
Model 2				
ABSFM	-126.00	0.88‡	-345.60	0.45‡
IMP	1385.40	1.15§	3600.40	1.43§
BR%	-6.85	0.93¶	-5.01	0.95¶
Fatigue-induced changes in gait kinetics				
APGRF			-0.01	0.99
IMP			-31.11	0.99§

ABSFM: Absolute peak free moment; IMP: Adduction angular impulse; FMBRAK: Free moment at peak braking force; BR%: Percent of stance involved in braking; APGRF: Peak braking ground reaction force; BL: injury model using both legs per subject; OL: injury model using one leg per subject

‡ $e^{\text{parameter}(0.001-0.000)}$

§ $e^{\text{parameter}(0.0001-0.0000)}$

¶ $e^{\text{parameter}(0.01-0.00)}$

DISCUSSION

The most important finding of the present study was that the identified kinetic risk factors for predicting ERLLP varied based on the injury classification used and the injury model employed. Models capable of accurately predicting ERRLP injury history based on pre-exercise kinetic gait variables were found using both BL and OL methods of modeling ERLLP injury but not for predicting ERLLP development prospectively. One significant model for predicting ERLLP history based on fatigue-induced changes in kinetic variables was found using OL but this combination of variables was not significant using the alternate BL injury model.

While there was similarity in the significant kinetic variables between models, not all significant predictive models were identical between BL and OL for predicting ERRLP injury history. One combination of kinetic variables, ABSFM, IMP and BR%, was significant in predicting previous ERLLP using either injury model. Values for ABSFM and IMP in the present study were similar to those reported in both a control and previous tibial stress fracture groups of female recreational distance runners in separate studies by Milner et. al [31] and Pohl, et al. [36]. Both of these studies found significantly higher ABSFM and a trend toward higher IMP in the previously injured group using a single leg per subject injury model (OL). However, in both OL and BL injury models in the present study, while the regression coefficient for IMP was positive, the regression coefficient of ABSFM was negative, indicating a decreased magnitude of peak rotational shear force in the injury group. Similarly, the regression coefficient for

BR% was negative indicating that a smaller percentage of the stance phase was devoted to deceleration of body mass in injured subjects.

A second model for predicting ERLLP history based on pre-exercise kinetic data was significant using BL. The ABSFM and IMP were significant in the same direction of magnitude as found in the previous model. The third component variable in this model was FMBRAK which had a negative correlation coefficient, indicating a decreased rotational shear force at peak breaking in the injury history group. The values for FMBRAK in the present study were similar to those describe in TSF subjects and controls by Milner et al. [31]. However, as with ABSFM in both models, the relationship between injury and magnitude of FMBRAK in the present study was opposite to that reported by Milner et al. [31].

When the second model was applied to OL, only ABSFM and IMP were significant in predicting ERLLP history. However, the regression coefficients for all three component variables for this model were identical in sign and similar in magnitude indicating a similar effect size for all three variables within the model for either BL or OL. Additionally, odds ratios for all three variables were similar for this model in both BL and OL, further indicating a similar effect size for all three variables (table 4). Percentages of concordant, discordant and tied pairs were also similar when applying this model to either OL or BL (table 3). Because the number of injured legs available for analysis when using the OL model is markedly decreased, it is reasonable to hypothesize that the non-significant contribution of FMBRAK (p=0.18) in the OL may have reached significance given a higher number of injuries. Therefore, regardless of the lack of significance for FMBRAK when applying model two to OL, based on the similar effect size for all variables evidenced by the parameter estimates, odds ratios, and percentages of concordant pairs, it is reasonable to consider this model equally effective using either BL or OL.

Differences in relationship of ABSFM and FMBRAK between NRI and RI subjects or legs in the present study compared to the findings of Milner et al. [31] and Pohl et al. [36] may be due to the inclusion of only rear-foot striking runners as their subjects. In the present study, subjects displayed a variety of initial foot strike patterns though no attempt was made to assess differences in kinetic variables between foot strike patterns. The inclusion of subjects with a variety of initial foot strike patterns may serve as a limitation of the present study as it is possible that ABSFM and FMBRAK differences between foot strike patterns may vary.

Differences in the relationship between ABSFM and FMBRAK magnitude and injury history in our study compared to previous studies that examined only TSF may support the theory that differences in mechanism exist between TSF and MTSS. In the present study, a broader injury definition was used which included both TSF and MTSS. Therefore, differences in ABSFM and FMBRAK between NRI and RI groups associated with MTSS may have served to counteract the relationship between ABSFM, FMBRAK and TSF described by previous authors [31, 36].

One combination of fatigue-induced changes in kinetic variables was significant based on OL data. Variables included in this model were IMP with a positive regression coefficient and APGRF with a negative coefficient. This relationship suggests that greater decreases in peak braking ground reaction forces and greater increases in IMP were associated with fatigue in subjects with a history of ERLLP. Increased IMP in pre-exercise gait kinetics has been associated with TSF history in previous research [31]. Previous studies have not investigated the changes in IMP associated with fatigue as a predictor of ERLLP history or MTSS. However, based on the changes in gait mechanics due to fatigue that have been observed previously, it is reasonable to assume that the increases in pre-exercise IMP associated with injury, which indicate increased rotational shear forces during stance, would be amplified by fatiguing exercise [14, 29].

Changes in VGRF owing to fatigue were not related, positively or negatively, to ERLLP injury history in the present study. Gerlach et al. [14] reported smaller decreases in VGRF in previously injured subjects following a fatiguing treadmill protocol compared to those with a history of lower extremity injury. However, in their study, ERLLP was not assessed specifically in their injury definition which included low back, knee, calf, ankle and foot pathologies. Further, these authors assessed kinetic changes related to fatigue using a treadmill equipped with piezoelectric force platforms which served as a limitation of the study since kinematic, kinetic and tibial strain differences between treadmill and over gfround running have been documented [28, 34, 42].

The greater decrease in APGRF owing to fatigue associated with RI in the present study may be associated with greater changes in running form. Miller et al. [30] reported that increases in knee flexion at heel-strike were more pronounced in runners with a history of iliotibial band syndrome at the end of an exhaustive treadmill run compared to controls. Derrick et al. [12] found that kinematic gait changes, marked by increased knee flexion as fatigue progressed, allowed for increased impact attenuations. Though not assessed in the present study, increases in knee flexion allowing for greater impact attentuation could serve to describe the fatigue-related decreases in APGRF associated with ERLLP injury history.

When applied to BL, neither of the variables in this model was significant with dissimilar regression coefficients and odds ratios. Because the significant model was derived using the smaller sample of the OL model, the non-significance found using BL was not related to a limited number of injured legs, as may have been the case in the pre-exercise models. However, one possible explanation for this difference may be due to the effect of the gait characteristics of the RI leg on the NRI leg in subjects with a history of unilateral injury. The affect of previous unilateral injury may serve to more notably alter the gait characteristics of the NRI leg following fatigue and cloud the differences found between RI and NRI legs when using the BL model. This affect does not serve as a confounding factor when using the OL model as unilateral NRI legs are not considered in either group.

No significant models were found for predicting the development of ERLLP from pre-exercise or fatigue-induced kinetic data using either the BL or OL. None of the significant models developed for predicting previous injury remained significant when applied to the prospective injury data and the effect sizes, as indicated by the magnitude and sign of the regression coefficients as well as the odds ratios, were markedly different (Table 6). This finding agrees with those of Gerlach et al. [14] who reported that the kinetic factors associated with previous injuries to the lower extremity were not found in subsequent prospective analysis of the same population. The authors concluded that the differences between retrospective and prospective analyses indicated that the kinetic differences associated with previous injury were the result of the injury itself as opposed to the cause [14]. Similarly, in the present study, the incongruity between retrospective and prospective analyses may indicate that the pre-exercise kinetic characteristics and fatigue-induced kinetic changes associated with ERLLP history occurred as the result of the previous injury.

It is also possible that the inability to produce a significant model for predicting ERLLP injury development may be related to the broad injury definition used in the present study. While several of the main kinetic variables assessed in the present study have been shown to be significantly associated with TSF history [31, 36], the relationship between these variables and MTSS, the other component of ERLLP contained in our injury definition, has not been established. Though not specifically assessed in the ERLLP Injury History Questionnaire (appendix B), a number of subjects anecdotally reported previous ERLLP based on a diagnosed TSF. However, none of the ERLLP injuries reported during the three month prospective analysis was diagnosed as TSF. Therefore, a significant relationship between injury history and kinetic variables such as ABSFM, IMP and FMBRAK may be expected based on the representation of TSF in the retrospective data. However, if notable differences in mechanism do exist between TSF and MTSS, the same relationships between these variables and MTSS may not exist. Thus, in the present study, the incongruity between identified retrospective and prospective kinetic variables may be attributable to differences in injury mechanism between the pathologies included in the broad definition of ERLLP.

Injury incidence in the present study was similar to those reported previously [4, 24, 35, 43, 47]. Among these subjects, 42% reported previous ERLLP and 26% subsequently developed ERLLP during the competitive season that was significant enough to limit sport participation. This rate is higher than the 18% prospective incidence reported by Willems et al. [43] in active college females using a similar injury definition as employed in the present study but is not unexpected as our subjects were elite athletes engaged in daily sport-specific training.

No restrictions to study participation were employed based on event participation. Subjects were only required to be current members of the NCAA Division I track & field team being studied. However, this inclusion criterion resulted in participation by subjects from a broad range of events and may have served as a limitation in the present study as training regimens and weekly running volume varied greatly between these groups. Though not quantified, it was noted during data collection that foot strike patterns were similar among subjects within a certain event but variable between event groups. During kinetic trials, subjects did not wear a standardized shoe type. The possible differences created by the use of several shoe types may constitute a limitation of the present study. However, the variability introduced by different shoe types can be exceeded by individual subject adaptations [10].

In summary, as hypothesized, data from the present study demonstrate that kinetic free moment variables shown previously to be associated with TSF history were also associated with previous ERLLP in collegiate female track & field athletes and changes in kinetic variables due to fatigue served as significant predictors of ERLLP. However, in the case of ABSFM and FMBRAK, the magnitude of this relationship was converse to previous reports possibly revealing differences in mechanism between TSF and MTSS or differences in FM mechanics between differing foot-strike patterns.

Though similar, the models for predicting previous ERLLP differed between BL and OL injury models. However, effect sizes for variables included in significant pre-exercise models of retrospective injury were comparable for both BL and OL, suggesting, as hypothesized, similar efficacy for predicting ERLLP history. In contrast though to the research hypothesis, modeling of ERLLP history from fatigue-induced gait changes was not similar between OL and BL.

No significant models for predicting ERLLP development were found and significant retrospective models were not significant when applied to prospective injury data with markedly different effect sizes in all cases, suggesting that kinetic differences were the result of previous injury instead of the cause. This finding is converse to hypothesized relationships between injury classifications (retrospective vs. prospective). Further research is needed to identify predictive models for the development of ERLLP as the previous research using these kinetic variables has involved retrospective analysis and may not be appropriately applied to prospective analysis.

In conclusion, within this population, BL and OL models appear equally effective for developing retrospective injury models using pre-exercise data. While fatigue-induced changes in gait kinetics do appear related to ERLLP history, only the OL model appears appropriate for this type of analysis. Risk factors associated with previous ERLLP and its components using either OL or BL should not be assumed to be associated with subsequent injury. However, the sample used in the present study may be the most appropriate for studying ERLLP based on incidence rates among female runners, the differing relationships found between gait kinetics and ERLLP depending on injury classification and model may not be found in other groups. Finally, differences between identified ERLLP risk factors in the present study and TSF risk factors reported previously indicate that further research into the specific mechanisms underlying TSF and MTSS is needed to determine if combining these pathologies under the heading ERLLP in future studies is appropriate.

PART II

REVIEW OF LITERATURE

Due to the lack of a clear understanding regarding the mechanisms underlying exercise related lower leg pain (ERLLP), the primary focus of research in this area addresses the risk factors associated with the clinical outcomes of ERLLP pathologies. These studies have used both retrospective and prospective research designs to assess both static foot postures and dynamic gait mechanics to examine ERLLP risk factors. However, due to limitations imposed by research designs or by the dependent variables chosen for study, the large majority of these studies have had significant shortcomings. These limitations have included failure to assess injury development prospectively using kinetic variables, failure to analyze subsequent changes in gait mechanics owing to fatigue and failure to consider important kinetic variables related to free moment, the vertical force moment representing rotational shear between the foot and running surface during stance associated with pronation.

Retrospective Research Designs

A number of studies have examined the relationship between gait mechanics and ERLLP pathologies using a retrospective research design. One of the early attempts to assess factors associated with overuse injuries in the lower extremity was that of Viitasalo and Kvist [41] who examined standing and running foot characteristics in active males with and without a history of shin splints. Though the term shin splints is no longer preferred, this diagnosis represents ERLLP due to MTSS or another related pathology. A control group of 13 males (mean age 30.6±7.7 years) was compared to two experimental groups, a group with a history of "bad shin splints" (n=13; mean age 23.8±7.1 years) and a group with a history of "slight shin splints" (n=22; mean age 19.8±5.7 years). Standing Achilles angle, passive subtalar joint motion and subtalar joint motion during running at 3.9 $m \cdot s^{-1}$ on a treadmill were assessed for all subjects. Running data were collected using a 16 mm LoCam camera filming at 100 frames per second and a four point marker set on the posterior shank and foot. One way ANOVA and independent t-tests indicated that foot mechanics were significantly different between subjects with and without a history of shin splints. Subjects in the combined shin splints group (either "bad" or "slight") demonstrated significantly greater standing Achilles angle as well as greater passive subtalar inversion, eversion and total excursion than controls. Additionally, subjects with a previous history of shin splints demonstrated greater Achilles angle at heel strike and greater eversion excursion during treadmill running than controls. The authors concluded that the data supported the hypothesis that structural and functional differences exist between athletes with and without a history of shin splints.

Messier and Pittala [27] expanded on the previous study using similar methods. In their study, control subjects with no previous overuse injuries related to running (n=19) were compared to subjects who were suffering from shin splints (n=17), plantar fasciitis (n=15), or IT band friction syndrome (n=13) at the time of testing as diagnosed clinically by an orthopedic surgeon and Board of Certification Certified Athletic Trainer (BOCATC). Additionally, comparisons between injured and control groups during analysis were made individually by pathology. Both of these aspects make this study unique since subsequent studies have generally only examined subjects who were injury free at the time of testing and have typically grouped different pathologies during analysis. All subjects had at least a one year history of running at least 10 $m \cdot wk^{-1}$. Measured anthropometric variables included medial longitudinal arch characteristics, plantar and dorsiflexion range of motion, leg length differences, Q-angle and hamstrings and leg flexibility. Rearfoot biomechanical data, including maximum pronation, total rearfoot movement, time to maximum pronation and maximum pronation velocity were assessed using a single 16-mm camera recording at 200 fps. Data were collected during the fifth minute of running on a treadmill at a speed determined by each subjects' reported training intensity. Plantar fasciitis subjects demonstrated significantly higher plantar flexion range than control subjects while shin splints subjects demonstrated significantly increased pronation rate and excursion over controls. No other anthropometric or biomechanic variables were significantly associated with any of the identified pathologies. However, because biomechanical data were assessed using only a single camera, the described differences in pronation rate and excursion were based on the uniplanar movements of the rearfoot and may not accurately represent triplanar changes occurring during loading.

In a similar manner, Hreljac et al. ([18] examined the relationship between gait mechanics and overuse injuries at or below the knee resulting from running without distinguishing between pathologies. The authors justified this lack of differentiation based on the lack of evidence associating specific anatomic or biomechanical abnormalities with specific injury patterns. Static foot postures, anthropometric measures and dynamic gait variables were assessed in two groups of 20 subjects each, one group with a history of at least one lower extremity injury attributable to running and the other group who had never suffered a running related overuse injury. Static variables included longitudinal arch height, footprint index and hamstrings and ankle flexibility. Ground reaction forces were assessed using a force platform sampling at 480 Hz and dynamic rearfoot motion was assessed using a simple four reflective marker set and a four camera motion analysis system sampling at 120 Hz. Subjects completed one trial for each foot running across the force platform at a rate of 4.0 $m \cdot s^{-1}$. Among static variables, only hamstrings flexibility, as measured by the sit and reach test, was significantly different between injury history groups with injured subjects demonstrating decreased flexibility. Among biomechanical variables, only vertical peak impact force and vertical peak loading rate were significantly different between groups though pronation rate was lower in the injury history group at a level approaching significance ($p=0.08$). The authors concluded that a running stride characterized by low impact forces and a moderately rapid rate of pronation produces a reduced risk of overuse injury. However, similar to Messier and Pittala [27], the kinematic model used to assess pronation/supination consisted of a simple 4 reflective marker set on the posterior shank and the triplanar motions of pronation and supination were defined based on changes occurring only in the frontal plane. Therefore, the veracity of the authors' conclusions regarding pronation characteristics related to injury is unclear in light of Messier and Pittala's [27] findings and subsequent research that has produced conflicting results.

One of the more commonly examined pathologies included under ERLLP has been tibial stress fractures. Crossley et al. [10] examined the relationship between stress fracture history, ground reaction forces and bone parameters in 46 trained male runners (mean age 24.7 ± 5.5 years). Twenty-three subjects with a history of tibial stress fracture as reported from patient records were compared to a subject matched control group for subject age, height, weight, years of running, weekly training volume, competitive distance and performance. Ground reaction forces were collected for all subjects through 10 trials of running over a force platform at $4.0 \pm 0.4\ \mathrm{m \cdot s^{-1}}$ while wearing their normal running shoes. Bone density was measured using dual energy x-ray absorptiometry and bone geometry collected via CT scan was used to calculate expected bone strength. No differences were found between subjects with a history of tibial stress fracture and their matched controls for any of the ground reaction forces or for unadjusted bone parameters. However, with adjustments for body mass and height as covariates, subjects with a history of tibial stress fracture possessed significantly narrower tibiae with significantly smaller cross sectional area. The authors concluded that smaller tibial cross-sectional area was a useful predictor of risk for tibial stress fracture and the development of simple methods to assess bone geometry might aid in identification of individuals at risk for injury.

Bennell et al. [3] reported similar findings from examining ground reaction forces and bone parameters in 36 trained female runners between 18 and 44 years of age. Thirteen subjects had a history of healed tibial stress fracture as diagnosed by physician based on clinical exam and positive results of a triple phase isotope bone scan. As in the previous study from this group [10], ground reaction forces were collected for all subjects through 10 trials of running over a force platform at 4.0 ± 0.4 $m \cdot s^{-1}$ while wearing their normal running shoes. Bone density was measured using dual energy x-ray absorptiometry and bone geometry collected via CT scan was used to calculate expected bone strength. No differences were found between subjects with or without a history of tibial stress fracture for any ground reaction forces or bone parameters. The authors concluded that risk factors among females for developing tibial stress fractures were not represented by the parameters studied.

Conversely, Milner et al. [32] recently reported differences in ground reaction forces between those with and without a history of tibial stress fracture. Twenty female runners (age 26 ± 9 years; running 46 ± 11 $km \cdot wk^{-1}$) with a history of tibial stress fracture were compared to a group of matched controls (age 25 ± 9 years; running 47 ± 16 $km \cdot wk^{-1}$). Kinematic data were captured at 120 Hz using a 6 camera motion capture system simultaneously with kinetic data using a force platform and a tibial accelerometer, both sampling at 960 Hz. Subjects completed 5 trials of running at 3.7±0.5% $m \cdot s^{-1}$ to collect biomechanical data. No kinematic differences were found between groups for ankle stiffness or knee joint excursion. Knee joint stiffness was higher in subjects with a history of tibial stress fracture at a level approaching significance (p=0.054). In agreement with previous studies [3, 10], the majority of the ground reaction force variables, including peak impact, were not significantly different between groups. However, instantaneous and average loading rate were significantly lower in the control group, in opposition to previous findings.

Previous studies using a retrospective research design have examined the relationship between gait related risk factors and history of ERLLP pathologies. However, these studies have produced conflicting results related to differences in ground reaction forces and kinematics between those with or without a history of ERLLP. Despite these differences, the value of these studies has been the dynamic nature of the measured variables which better represents the demands of exercise than static measures of foot posture such as navicular drop. Unfortunately, the retrospective design of these studies prevents an understanding of the temporal relationship between the dependent and independent variables as the biomechanical differences observed could be either the cause or the effect of the pathology. This limitation has been addressed by other groups who have used a prospective research design to assess ERLLP risk factors.

Prospective Research Designs

Previous research examining ERLLP and its component pathologies using a prospective design is limited and has generally evaluated static foot posture variables. The work of Yates et al. [47], who examined the incidence and risk factors of developing MTSS in 112 Australian naval recruits during a 10 week basic training program, appears to be the first MTSS study to use a true prospective design. Static foot posture was evaluated using the Foot Posture Index which classifies foot type as pronated, normal or supinated based on eight foot measurements taken during balanced standing. During the 10 week training program, 18 women (52.9%) and 22 men (28.2%) developed MTSS indicating a significantly higher risk among females. Risk of developing MTSS among subjects who reported a previous history of MTSS was nearly twice as high as those with no previous history. Foot Posture Index scores were significantly higher in the MTSS group than in the control group indicating an increased pronatory foot type among those who developed MTSS during the training program. Based on their results, the authors concluded that attempts to control foot pronation through adjustments to shoe type and training surface may aid in reducing time lost due to MTSS. Additionally, the authors suggested that their results highlighted the need for differing training programs for male and female military recruits.

One of the first attempts to prospectively analyze MTSS was that of Bennett et al. [4]. This group analyzed static foot postures among 125 (57 men, 68 women) high school runners and recorded the incidence of MTSS development during a full cross-country season. Resting calcaneal position in stance, tibiofibular varum, active dorsiflexion and navicular drop of the 15 subjects (2 men, 13 women) who developed MTSS during the season were compared to that of 21 randomly selected controls. No significant differences were found between groups for any of the measured variables except for navicular drop, which was greater in the MTSS group, and gender, in which the rate of MTSS incidence was higher among females. Logistic regression using navicular drop and gender differences between groups produced an equation which accurately predicted MTSS in 76% of cases (R^2=.465). However, the initial research design was prospective in nature, and the only significantly different measured variable (navicular drop) was assessed after MTSS was detected. Therefore, this analysis was, in reality, a retrospective investigation since it is not possible to determine the temporal relationship between injury and the differences in navicular drop found between groups.

A similar examination of the relationship between navicular drop and exercise-related leg pain (ERLP) pathology was conducted by Reinking et al. [39] in collegiate cross-country runners. Retrospective analysis of the relationship between navicular drop, gastrocnemius/soleus length and ERLP injury history was performed using 63 collegiate cross-country runners (30 male, 33 female; mean age 19.4 ± 1.2 years). From this same population, a subset 32 subjects from the same cross-country team (13 male, 19 female) were tracked throughout the fall competition season for the development of ERLP as diagnosed clinically by the team medical staff. Results of the retrospective analysis using x^2 and independent t-tests indicated that ERLP incidence was common among subjects (52%) but that neither navicular drop nor gastrocnemius/soleus length were significantly different between injury history groups. Further, no differences existed in age or, years running or orthotic use between groups. Prospective analysis indicated that 80% (8 out of 10) of subjects who developed ERLP during the season had a history of ERLP; 70% experienced medial leg symptoms and 50% experienced symptoms bilaterally. Differences in navicular drop between groups for prospective analysis were not reported. However, only two of those who developed ERLP used orthotics while four others with ERLP history who used orthotics did not subsequently develop symptoms during the study period. The authors contended that these data support the premise that orthotic use was effective in reducing ERLP in their subjects even though foot pronation, as measured by navicular drop, was not associated with history of ERLP. Though this study contained a prospective component, its main outcomes were based on retrospective analysis of injury history and only examined static foot postures in these subjects.

Reinking [38] subsequently examined ERLP with a true prospective model using navicular drop in 76 female collegiate athletes (mean age 19.3±1.0 years) from four NCAA division I sports (cross-country, field hockey, volleyball and soccer). Injury and menstrual history, eating behaviors, anthropometric measures, gastrocnemius/soleus length and navicular drop were assessed at the start of the competitive season for all subjects. Athletes were tracked during the competitive season for the development pathologies related to ERLP as diagnosed clinically by their medical staff and, in cases of suspected stress fracture, diagnostically using triple-phase bone scan. Following the season, 20 athletes with ERLP and 20 matched controls underwent bone mineral density assessment using standard DEXA testing. Twenty of the 58 subjects reported previous ERLP suffered subsequent injury during the season, an overall prospective injury rate of 26.3%. Soccer athletes suffered ERLP at a significantly lower rate than other sport subjects (3.4% and 27.3-50%, respectively). A history of ERLP was significantly associated with ERLP incidence, as was navicular drop which was significantly greater in ERLP subjects. Height, weight, BMI, age, muscle length, eating behaviors and bone mineral density were not significantly different between ERLP and non-ERLP groups using x^2 and independent t-tests. The authors concluded that increased foot pronation, ERLP injury history and sport affiliation were associated with increased risk of ERLP.

The limitations of the previous analysis by Bennett et al. [4] were addressed in a subsequent assessment by Plisky et al. [36] who prospectively examined the relationship between MTSS and navicular drop in high-school cross country runners. Height, weight, body mass index (BMI), foot length, navicular drop and running, training and orthotic use history was assessed in 105 high-school cross country runners (59 male, 46 female; mean age 16±1.0 years) at the beginning of the competitive season. Subjects were then tracked during the ensuing season for the development of MTSS as diagnosed clinically by a BOCATC. Injury rate during the 13 week season was 15.2% (16 runners incurred 17 MTSS injuries), similar to that reported previously [4]. However, no differences in MTSS injury rate were found between male and female runners ($p=.11$). Results of multivariate logistic regression indicated that only BMI was significantly associated with MTSS incidence after controlling for orthotic use. The most important finding of this study was that navicular drop and foot length were not significant predictors of MTSS development, in opposition to the findings of Bennett et al. [4].

Only one group has prospectively investigated risk factors for ERLLP using kinematic and kinetic gait analysis. Willems et al. [44] examined the relationship between gait mechanics and ERLLP in 400 college freshman (241 men, 159 women; mean age 18.4 ± 1.1 years) participating in a required physical education program. Kinematic data were collected using seven infrared cameras during three trials running at $3.3 \pm 0.17\ \mathrm{m \cdot s^{-1}}$. Kinetic data were collected during these trials using a footscan pressure plate secured to a force platform. Additionally, static foot postures were assessed goniometrically for all subjects. Subject injury incidence, defined by the need to seek medical care or decrease physical activity due to the injury, was followed by a single physician over the three year study period during which 46 subjects (17 males, 29 females) developed ERLLP. Subjects who developed injuries other than ERLLP were excluded from analysis resulting in a control group of 167 subjects in the uninjured group. The authors concluded that ERLLP incidence was associated with an increase in total eversion and abduction excursion, eversion rate, and abduction rate during loading and flat foot stance, resulting in higher loading underneath the medial forefoot. Additionally, ERLLP was associated with increased re-inversion velocity and lateral roll-off as well as increased extension range-of-motion at the first metatarsophalangeal joint. However, no relationship was found between peak loading forces and injury, which has been debated in previous research. Baseline training and exercise volume between subjects was not controlled. The authors cited these as limitations of the study and suggested they be addressed in future research. However, despite these limitations, this study was the first study to prospectively examine risk factors associated with ERLLP and provides valuable insight into the relationship between gait mechanics and injury.

Subsequently, Willems et al. [46] reported the relationship between ERLLP and gait mechanics while shod in this same subject population. Using the same methodology described previously, the authors found that many of the significant difference found between the ERLLP and control groups in the barefoot condition were blunted in the shod condition. Significant differences between groups in the shod condition still existed for abduction excursion, re-inversion velocity and lateral roll-off. Additionally, maximal eversion was delayed (as a percentage of stance phase time) in the ERLLP group in the shod condition. Interestingly, the authors describe pronation as a single metric as opposed to individual reporting of its components of eversion, abduction and dorsiflexion as is the convention. This reported three dimensional pronation excursion was significantly higher in the ERLLP group. Based on the differences in gait mechanics associated with ERLLP between barefoot and shod conditions, the authors proposed future research include analysis of subjects in both states.

The research design limitations of previous retrospective studies has been addressed by several groups who used prospective designs to examine risk factors for ERLLP. However, these studies have generally measured static foot postures such as navicular drop and foot alignment which does not reflect the demands placed on the kinetic chain during exercise as accurately as dynamic gait analysis. Only one group has addressed the limitations of previous research by measuring dynamic gait variables using a prospective research design. However, these studies did not control for exercise exposure among subjects and, like the majority of research in this area, did not assess how changes in gait variables due to exercise may contribute to injury development.

Changes in Gait Mechanics Due to Exercise

Changes in gait biomechanics occurring due to exercise exposure have been well studied. However, these examinations have not generally examined the relationship between these changes and ERLLP pathologies. A rudimentary analysis of changes in gait mechanics over the course of a 3000 m timed trial was conducted by Elliott and Roberts [13]. Kinematic data were collected on 8 college runners (7 males; 1 female) at 500, 1300, 2100 and 2900 m using a high-speed camera recording at 100 fps. Velocities remained consistent over the course of the 3000 m trial and no significant differences were found in gait mechanics over the first three periods measured. During the fourth stage, subjects demonstrated significantly shorter stride lengths and higher stride rates. The leg angle at foot strike increased, thigh extension at push-off decreased and the trunk was carried further forward during the running cycle in fourth stage as well. The authors concluded that these changes in gait biomechanics resulting from fatigue would result in decreases in running efficiency and overall performance, though they did not address the possible effect these changes may have on running injuries.

Recent research has provided additional insight into the relationship between injury and exercise induced gait changes. Gerlach et al. [14] investigated changes in ground reaction forces occurring due to exhaustive treadmill exercise and the relationship to back and lower extremity injury in 87 trained female runners (mean age 36.5 ± 9.2 years). Vertical ground reaction forces were collected using a force measuring treadmill before and after a fatiguing graded exercise test. Significant decreases in impact peak, loading rate and stride rate, along with significant increases in stride length, were reported following the fatiguing treadmill test. These findings were in opposition to the authors' hypothesis. The relationship between fatigue induced kinetic changes and injury were examined both retrospectively, using a pre-test injury history questionnaire, and prospectively, via post-test follow-up assessments every three months for one year. No relationship was found between previous injury and pre- or post-fatigue peak impact ($p=0.85$) nor between injury and pre- or post-fatigue impact loading rate. However, when analyzed retrospectively, the latter relationships approached significance ($p=0.07$) with the injury group demonstrating higher values for impact loading rates. Retrospective analysis revealed a significant interaction between previous injury history and changes in impact loading rate due to fatigue. Decreases in impact loading rate were less pronounced in those reporting previous injuries signifying exposure to increased loading rates among injured subjects as they fatigue. However, this same relationship was not found during prospective analysis suggesting this difference in impact loading rate decrease between injury history groups was more likely an affect of the injury than a cause. Slightly, though still non-significantly, higher impact loading rates were found in those suffering knee and calf/foot/ankle injuries both retrospectively (p=0.09) and prospectively (p=0.08). Based on the limited strength of association between injury and kinetic changes occurring due to fatigue, the authors could not conclude that changes in impact forces contributed to a history or development of running injuries.

Using a more specific lower-extremity injury definition, Miller et al. [30] found significant differences in gait mechanics between controls and subjects with a history of iliotibial band syndrome (ITBS) following an exhaustive run. Gait mechanics of eight runners with a history of ITBS (mean age 27.5 ± 9.0 years) and a group of matched controls were assessed using an eight-camera optical capture system while running at a selected speed on a treadmill. Data were collected for 10 s every 2 min while the subjects ran to voluntary exhaustion. Knee flexion at heel-strike, maximum foot inversion and maximum knee internal rotation velocity were significantly higher in ITBS subjects at the end of the exhaustive run compared to controls. The authors concluded that these changes were consistent with theoretical models of ITBS development and may serve as kinematic discriminators for clinical assessment.

A clearer understanding of the relationship between biomechanical changes and ERLLP pathology was provided by Milgrom et al.'s [29] study of changes in tibial strain resulting from fatiguing exercise and the possible implications related to the development of tibial stress fractures. Strain gauge staples were surgically placed in the right mid-tibial diaphysis of four male subjects, ranging from 27 to 52 years of age. Following placement, subjects completed five hours of light exercise, including 50 m runs, jumping activities, treadmill walking and running, bicycle sprints, leg squats and step climbing, followed by collection of baseline strain data and ground reaction forces as the subjects walked over a 12 m walkway. Baseline right gastrocnemius isokinetic peak torque was assessed using a Biodex dynamometer. Following baseline data collection, subjects began a fatigue protocol which began with a 2 km run at self-selected pace followed by a repeated assessment of the previous baseline measures. After an hour rest, subjects completed a 30 km march at a forced pace of six km/h after which the baseline measures were again assessed. Repeated measures ANOVA indicated significant decreases in gastrocnemius peak torque following the 30 km march suggesting fatigue of the muscle. Additionally, significant increases ($p<0.05$) in tension strain, tension strain rate and compression strain rate with significant decreases in compression strain ($p<0.05$) were found following the fatigue protocol, despite the small sample size. The authors concluded that the strain data found in their fatigued subjects were well above those reported previously in rested subjects and that these changes may be a major contributing factor to the development of stress fractures in individuals who exercise in a fatigued state.

Though changes in gait biomechanics due to exercise exposure have been well documented, the relationship between these changes and ERLLP is not well understood. Only one study has examined exercise related biomechanical changes associated with the development of ERLLP due to stress fracture. This study used an invasive procedure to examine bone strain changes but did not examine stress fracture risk factors related to kinematic or kinetic changes. No studies have examined the relationship between ERLLP risk factors and kinematic or kinetic changes resulting from acute or chronic exercise exposure.

Use of Free Moment Variables in Gait Assessment

Though a limited amount of previous research has examined the association between FM kinetic variables, pronation kinematics and TSF, the relationship between FM and the more broadly defined ERLLP pathology has not been established. Due to the difficulties in measuring pronation kinematically, in pathologies in which the mechanism of injury involves rotational shear forces, FM has been shown to be a valuable indicator of pronation and pronation-related differences between groups.

Holden and Cavanagh [17] conducted one of the first studies that examined the relationship between FM and pronation kinematics. Free moment kinetics were examined in ten male recreational runners as they ran across a force platform at 4.5 ± 10% $m \cdot s^{-1}$ in three different pairs of specially fabricated running shoes. Each pair of shoes differed in their midsole construction so that the amount of wedge in the shoe created varying amounts of pronation during gait. Five trials were completed for each foot wearing each pair of shoes. Each subject wore the neutral shoe first followed by the valgus and varus pairs which were randomly ordered between subjects. While FM was highly variable between feet, findings with a given foot or footwear condition were repeatable. Peak FM magnitude and net angular impulse were both significantly higher from varus to neutral and from neutral to valgus conditions using a repeated measures ANOVA design. The authors concluded that FM could be used to detect relatively large within-subject changes in pronation.

Milner et al. [31] followed-up on the work of Holden and Cavanagh in examining the relationship between FM variables and TSF in a group of female runners. Twenty five female distance runners (age 28 ± 10 years; mileage 46 ± 15 $\text{km}\cdot\text{wk}^{-1}$) who were uninjured at the time of testing but had a history of TSF were compared to a group of age and mileage matched controls with no previous lower extremity fractures. Five trials were collected as the subjects ran across a force plate at 3.7 ± 5% $\text{m}\cdot\text{s}^{-1}$. Involved side kinetic data was collected for previously injured subjects and compared to gait data from the right side of the control group. All FM variables were normalized for subject height and weight to allow comparison between subjects. Peak adduction FM, FM at peak breaking force and absolute peak FM (peak FM whether adduction FM or abduction FM) were all significantly higher in the TSF group and FM impulse approached significance using a one-tailed t-test. Absolute peak FM was significantly predictive of TSF injury history using logistic regression modeling. The authors concluded that the increased FM values associated with previous TSF suggest the mechanism of injury for TSF may involve a rotational shear component. However, because this research used a retrospective model, a causative relationship between FM variables and TSF cannot be determined.

This group expanded their investigation of the relationship between TSF and FM by examining kinematic variables in conjunction with FM variables [37]. Thirty female runners (age 28 ± 10 years; mileage 41 ± 11 $\mathrm{km \cdot wk^{-1}}$) with a history of TSF were compared to a group of age and mileage matched controls as they ran at 3.7 ± 5% $\mathrm{m \cdot s^{-1}}$ while kinematic and kinetic data were collected using a force platform sampling at 960 Hz and a 6 camera VICON optical capture system recording at 120 Hz. An accelerometer was attached to the anterior medial aspect of the tibia for all trials. Five trials were used for each test limb. Data were collected on the involved side for the TSF group while a counterbalanced sample of limbs was used from the control group. Three dimensional rearfoot, knee and hip joint angles were calculated and FM variables normalized for height and weight. Logistic regression modeling was conducted to determine which variables were significant predictors of TSF injury history. Increased peak hip adduction, FM and peak rearfoot eversion were associated with an elevated risk of TSF history. Additional variables did not improve the predictive efficacy of the regression model. The authors concluded that the combination of risk factors associated with TSF history demonstrate the multifactorial nature of TSF injury. However, as in their previous study, the retrospective nature of the study imposes limitations on the ability to assign a causative relationship to the identified variables.

Research involving the use of FM variables to predict lower extremity overuse injury is limited. Examination has demonstrated a relationship between FM and pronation kinematics which in turn has been shown to be a risk factor for ERLLP. Further, increases in FM variables have been shown to be related to a history of TSF in female runners. However, these studies have limited their injury definition to TSF and the relationship between FM and ERLLP has not been established. Additionally, the retrospective nature of these previous studies prevents conclusions regarding the causative nature of the kinetic gait characteristics involved. Therefore, as with the preponderance of research using dynamic variables to examine the relationship between gait and ERLLP, FM variables should be examined using a prospective model to establish the possible role of rotational shear forces as a causative factor for injury.

APPENDIX A

INFORMED CONSENT FORM

INFORMED CONSENT
To Participate in a Research Study

Department of Kinesiology and Leisure Science, University of Hawaii at Manoa
1337 Lower Campus Road, PE/A Complex Rm. 231, Honolulu, HI 96822
Phone: 808-956-7606

I. INVESTIGATORS

Principle Investigators: Christopher Stickley, MA, ATC; Rachele Vogelpohl, ATC; Iris F. Kimura, PhD, ATC, PT

II. TITLE

The Effect of Exercise on Gait Related Risk Factors for Exercise Related Lower Leg Pain in Collegiate Female Athletes

III. INTRODUCTION

The following information is being provided to help you decide if you would like to participate in this study. This form may have words that you do not understand. If you have questions, please ask us.

The purpose of this study is to examine the movements and forces experienced during running as they relate to overuse lower leg pain. You are being asked to participate in this study because you are a highly competitive, well trained track and field athlete.

IV. DESCRIPTION OF PROCEDURES

You will be asked to fill out an injury history questionnaire prior to data collection. You will then be asked to report to the University of Hawaii at Manoa, Kinesiology and Leisure Science Laboratory for testing. Your height, weight and skinfold thickness will be measured by a female member of the research team who is a certified athletic trainer. Next, reflective markers will be placed on several landmarks on your body (ex. shoulders, lower back, hips, thighs, knees, shins, ankles, and feet). You will be asked to wear spandex, sports bra and your normal running shoes. Marker placement will be performed by a female certified athletic trainer. You will be asked to run at a moderate pace (approximately a 6:45 min/mile pace) down a 15 m runway. You will perform three successful trials for each leg while wearing normal running shoes and three successful trials for each leg while barefoot (approximately 12-15 trials total). Following these trials you will be asked to complete a maximal oxygen uptake test (VO_{2max}) on a treadmill. Reflective markers will then be replaced and you will be asked to complete the 15 m trials a second time. You will have time prior to running to warm up and stretch, as well as time to get familiar with the procedures. This entire procedure will take approximately 45 minutes.

You will be asked to repeat this procedure approximately 3 months after the initial testing. During the 3 months between testing, members of the research team who are certified athletic trainers will evaluate you at the UH Athletic Department facilities once every 2 weeks for the development of lower leg pain. This evaluation will include questions and hands-on injury evaluation.

V. RISKS

Due to the level of physical activity involved, there is a risk of injury. You may have muscle soreness and/or pain after testing. You may also have some discomfort, muscle cramping or shortness of breath while testing. There is a very remote chance of cardiac arrest and/or death. The investigators are BOC certified athletic trainers and First Aid/CPR/AED trained. In the event of any physical injury from the research, only immediate and essential medical treatment is available including an AED. First Aid/CPR and a referral to a medical emergency room will be provided.

You should understand that if you are injured in the course of this research process that you alone will be responsible for the costs of treating your injuries.

VI. BENEFITS

You may not receive direct/immediate benefits. However, you will obtain information regarding your running characteristics and aerobic exercise capacity. Results of this study may assist athletic trainers, coaches and sport biomechanists in preventing future injuries in female track and field athletes.

VII. CONFIDENTIALITY

Your research records will be confidential to the extent permitted by law. Agencies with research oversight, such as The University of Hawaii Committee on Human Studies, have the right to review research records.

An identification number will be used to identify you during the study, which will be known only to you and study personnel. In addition, all data and subject (identity) information will be kept under lock and key in the Department of Kinesiology and Leisure Science at the University of Hawaii at Manoa. These materials will be permanently disposed of in a period not longer than 5 years. You will not be personally identified in any publication arising from this study. Personal information about your test results will not be given to anyone without your written permission.

VIII. CERTIFICATION

I certify that I have read and I understand the foregoing, that I have been given satisfactory answers to my inquiries concerning the project procedures and other matters and that I have been advised that I am free to withdraw my consent participation and to discontinue participation in the project or activity at any time without prejudice.

I herewith consent to participate in this project with the understanding that such consent does not waive any of my legal rights, nor does it release the principle investigator or institution or any employee or agent thereof from liability for negligence.

I attest that I am not currently limited from full participation in my chosen sport due to injury.

I attest that I do not believe that I am currently pregnant and that should I become pregnant during participation in this study that I will voluntarily withdraw from further participation.

If you have any questions related to this study, please contact any of the principle investigators: Dr. Iris F. Kimura at 956-3797, Christopher Stickley at 956-3798, or Rachele Vogelpohl at 956-8793 at any time.

____
Subject ID Number

____ _______________
Signature of Participant Date

If you cannot obtain satisfactory answers to your questions, or have complaints about your treatment in this study, please contact: Committee on Human Subjects, University of Hawai'i at Manoa, 2540 Maile Way, Honolulu, Hawaii 96822, Phone (808) 956-5007.

APPENDIX B

ERLLP INJURY HISTORY FORM

ERLLP INJURY HISTORY QUESTIONAIRRE

Name ______________________________ **ID** _____ **Date** _______

Age: _____ **Height:** _______ **Weight:** _______ **Skinfold Thickness:** __________

Orthotics in Running Shoes: **Y** **N**

Primary Event: **Sprint** **Middle Distance** **Distance** **Jumper** **Thrower** **Heptathlon**

Training History

I currently spend approximately _____ per week training.

_____ 0-5 hours
_____ 5-10 hours
_____ 10-15 hours
_____ 15-20 hours
_____ Over 20 hours

I currently run an average of approximately _____ per week.

_____ 0-5 miles
_____ 5-10 miles
_____ 10-15 miles
_____ 15-20 miles
_____ Over 20 miles

Injury History

1. **YES** **NO** I have experienced pain in my left lower leg (below my knee and above my ankle) resulting from participating in training, practice or competition in my sport. (Circle "Yes" or "No" – **DO NOT include pain that resulted from a single specific injury episode such as a bruise, sprain or broken bone)**

If **YES**, please answer questions 2 & 3 below. IF YOU HAVE EXPERIENCED MORE THAN 1 INJURY, ANSWER QUESTIONS 2 & 3 BELOW REGARDING YOUR MOST RECENT INJURY.

If **NO**, skip to question 4 below.

2. The pain in my left lower leg occurred:

_____ during the last 6 months
_____ between 6 months and 1 year ago
_____ between 1 and 2 years ago
_____ more than 2 years ago

3. The pain in my left lower leg:

_____ was not serious enough to seek medical care or treatment from a physician or athletic trainer
_____ was serious enough to get treatment (ice, taping, anti-inflamatory medication, etc.) from a physician or athletic trainer but NOT serious enough to require any change in training, practice or competition in my sport
_____ required me to decrease my training (amount or intensity) but I did not have to completely miss or "sit-out" any of my training, practice or competition in my sport
_____ required me to completely miss or "sit-out" some of my training, practice or competition in my sport

4. **YES** **NO** I have experienced pain in my right lower leg (below my knee and above my ankle) resulting from participating in training, practice or competition in my sport. (Circle "Yes" or "No" – **DO NOT include pain that resulted from a single specific injury episode such as a bruise, sprain or broken bone)**

If **YES**, please answer questions **5 & 6** below. IF YOU HAVE EXPERIENCED MORE THAN 1 INJURY, ANSWER QUESTIONS 5 & 6 BELOW REGARDING YOUR **MOST RECENT** INJURY.

If **NO**, you are finished.

5. The pain in my right lower leg occurred:

_____ during the last 6 months
_____ between 6 months and 1 year ago
_____ between 1 and 2 years ago
_____ more than 2 years ago

6. The pain in my right lower leg:

_____ was not serious enough to seek medical care or treatment from a physician or athletic trainer
_____ was serious enough to get treatment (ice, taping, anti-inflamatory medication, etc.) from a physician or athletic trainer but NOT serious enough to require any change in training, practice or competition in my sport
_____ required me to decrease my training (amount or intensity) but I did not have to **completely** miss or "sit-out" any of my training, practice or competition in my sport
_____ required me to completely miss or "sit-out" some of my training, practice or competition in my sport

APPENDIX C

BI-WEEKLY ERLLP INJURY HISTORY FORM

BI-WEEKLY ERLLP INJURY HISTORY QUESTIONAIRRE

Subject ID ______________________ **Date** _______

Training

During the past 2 weeks, I spent approximately _____ per week training.	During the past 2 weeks, I ran an average of approximately _____ per week.
_____ 0-5 hours	_____ 0-5 miles
_____ 5-10 hours	_____ 5-10 miles
_____ 10-15 hours	_____ 10-15 miles
_____ 15-20 hours	_____ 15-20 miles
_____ Over 20 hours	_____ Over 20 miles

Injury History

1. **YES** **NO** During the past 2 weeks, I have experienced pain in my left lower leg (below my knee and above my ankle) resulting from participating in training, practice or competition in my sport. (Circle "Yes" or "No" – **DO NOT include pain that resulted from a single specific injury episode such as a bruise, sprain or broken bone)**

If **YES**, please answer question 2 below.

If **NO**, skip to question 3 below.

2. The pain in my left lower leg during the past 2 weeks:

_____ was not serious enough to seek medical care or treatment from a physician or athletic trainer
_____ was serious enough to get treatment (ice, taping, anti-inflamatory medication, etc.) from a physician or athletic trainer but NOT serious enough to require any change in training, practice or competition in my sport
_____ required me to decrease my training (amount or intensity) but I did not have to **completely** miss or "sit-out" any of my training, practice or competition in my sport
_____ required me to completely miss or "sit-out" some of my training, practice or competition in my sport

3. **YES** **NO** During the past 2 weeks, I have experienced pain in my right lower leg (below my knee and above my ankle) resulting from participating in training, practice or competition in my sport. (Circle "Yes" or "No" – **DO NOT include pain that resulted from a single specific injury episode such as a bruise, sprain or broken bone)**

If **YES**, please answer question 4 below.

If **NO**, you are finished.

4. The pain in my right lower leg:

_____ was not serious enough to seek medical care or treatment from a physician or athletic trainer
_____ was serious enough to get treatment (ice, taping, anti-inflamatory medication, etc.) from a physician or athletic trainer but NOT serious enough to require any change in training, practice or competition in my sport
_____ required me to decrease my training (amount or intensity) but I did not have to **completely** miss or "sit-out" any of my training, practice or competition in my sport
_____ required me to completely miss or "sit-out" some of my training, practice or competition in my sport

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