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Understanding the etiology of the posteromedial tibial stress fracture

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ABSTRACT

Previous human in vivo tibial strain measurements from surface strain gauges during vigorous activities were found to be below the threshold value of repetitive cyclical loading at 2500 microstrain in tension necessary to reduce the fatigue life of bone, based on ex vivo studies. Therefore it has been hypothesized that an intermediate bone remodeling response might play a role in the development of tibial stress fractures. In young adults tibial stress fractures are usually oblique, suggesting that they are the result of failure under shear strain. Strains were measured using surface mounted unstacked 45° rosette strain gauges on the posterior aspect of the flat medial cortex just below the tibial midshaft, in a 48 year old male subject while performing vertical jumps, staircase jumps and running up and down stadium stairs. Shear strains approaching 5000 microstrain were recorded during stair jumping and vertical standing jumps. Shear strains above 1250 microstrain were recorded during runs up and down stadium steps. Based on predictions from ex vivo studies, stair and vertical jumping tibial shear strain in the test subject was high enough to potentially produce tibial stress fracture subsequent to repetitive cyclic loading without necessarily requiring an intermediate remodeling response to microdamage.

Introduction

Stress fractures are a major musculoskeletal problem among both athletes and military recruits [1,2]. During demanding elite infantry basic training a 31% incidence has been reported, with the tibia being the most affected bone [2]. Stress fracture is initiated by cyclic overloading of bone. The level of the loading and the number of loading cycles necessary to cause human cortical bone fatigue failure and stress fracture have been the subject of ex vivo studies [3–6]. Most of these studies have used specimens from the femoral midshaft and employed single modalities of loading. They have found that the secant modulus degradation of human femoral cortical bone in fatigue loading greatly increases above the strain threshold of 2500 microstrain when loaded in tension and 4000 microstrain when loaded in compression [4,5]. Turner et al. studied the shear fatigue properties of human femoral cortical bone in pure shear testing [7]. They found it to be very weak in shear and subject to a shorter fatigue life when repetitively loaded in shear than those reported by Patin et al. when loaded in tension or compression [5].

The first human in vivo bone surface strain measurements were reported by Lanyon et al. in 1975 [8]. Because of the direct recording technology used in the study, in which subjects were tethered to the recording equipment, measurements of vigorous activities were necessarily limited in scope. During treadmill barefoot running, they recorded maximum tibial compression strains of 450 and maximum tension strains of 800 microstrain.

A subsequent study, focused on the etiology of tibial stress fractures, measured in vivo tibia strains using a mobile recording system during activities mimicking those done by infantry recruits [9]. During level walking shear strains did not exceed 900 microstrain and during sprinting they did not exceed 1600 microstrain. The highest strain measured was 2000 microstrain in shear during zig zag uphill running. Based primarily on ex vivo tension and compression fatigue loading data, it has been concluded that even during strenuous activities, strains are not in themselves sufficiently high to cause stress fracture [2,6]. It has been hypothesized that an intermediate bone remodeling response might play a role in the development of tibial stress fractures [6]. According to this model, bone when exposed to higher than usual strains, sustains microdamage and attempts to repair itself by remodeling. In this case bone resorption precedes the deposition of new bone. During this resorption phase the bone is weakened, and repetitive high strains are more likely to cause a stress fracture.

The goal of the present report is to assess axial and shear strains at the tibial bone surface during vigorous activity and use it as a basis to better understand the etiology of posteromedial tibial stress fracture. For this purpose data from activities performed during the 1994 Burr et al. experiment, but never previously analyzed, are presented and analyzed [9].

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Methods

Strain gauge recordings

The strain gauge recordings were made on a 48 year-old male volunteer. The study protocol received institutional approval from the Helsinki Committee on Human Experimentation. The surgical procedure was performed under local anesthesia and two unstacked, 45° rosette strain gauges (Micromeasurements EA-06-015-RJ-120, Measurement Group, Inc. Raleigh, NC) were bonded to the posterior aspect of the flat medial tibial cortex, using polymethyl methacrylate [10]. The length of the subject's tibia, 39 cm, was determined on an AP X-ray of the tibia prior to the surgery. One gauge was bonded at a point 18.5 cm above the ankle joint and the second at a point 16.5 cm above the ankle joint. Strain gauge data were recorded from the subject on a four channel FM analog tape recorder (TEAC HR-40; Tokyo, Japan) from the proximal strain gauge. The tape recorder, an amplifier and a battery pack were carried by the subject in a back pack (Fig. 1).

Measurements were made during the following activities:

1) Three repetitive standing vertical jumps with a jump height goal of 30 cm.
2) Running up and down stadium stairs of a height of 15 cm and a depth of 37 cm.
3) Without practice, the subject was requested to serially jump down from as many steps of a concrete staircase onto an asphalt surface as he could, beginning from the first step. Recordings were made during jumps from a height of one step to four steps. The first step was a height of 22 cm and a depth of 36 cm; the second to fourth steps were 42, 58 and 74 cm from the ground with a total horizontal distance of 132 cm. The subject performed this activity only once.

Fig. 1. Study subject with mobile recording system carried in back pack.

Data analysis

The files were originally saved in a unique binary format by SnapShot software (HEM, Troy, MI) provided with the analog-to-digital converter. For the current study, a computer program was written to convert the unique binary format into an ASCII format. The accuracy of the conversion was validated by comparing a series of files from the original study in which data had been saved both in the unique binary format and ASCII format.

Raw data were analyzed using a Fast Fourier Transform function (Matlab, The MathWorks, Inc.) to identify the spectral density of the various frequencies. A cutoff frequency of 20 HZ was chosen as the fundamental frequency at which all in vivo activities can be included and hence all frequencies above this range were considered to be noise. The principal and shear strain in microstrain were calculated for each activity. For running up stairs the mean value $\pm$ SD for 10 stairs and for running down stairs the mean $\pm$ SD of 13 stairs were calculated. For vertical jumping to 30 cm the mean $\pm$ SD of three jumps was calculated.

Results

The subject experienced no pain at the surgical site during the activities and comfortably performed all scheduled activities. The strain gauges were removed under local anesthesia at the end of the experiment. At the time of surgical removal both gauges were found to be functioning properly, firmly bounded to the tibia and all wires and connections were intact.

Table 1 summarizes the compression, tension and shear strains for stair jumping. The highest strains occurred during the initial jump from the first stair and there was no relationship between the height of the staircase jump and the strain recorded. During the landing from four steps the subject made an initial landing and then stumbled forward and took an additional step before he reached a stable position. Values for the first landing step and the second stumble step are presented separately.

Table 2 summarizes the mean and standard deviation of compression, tension and shear strains for vertical standing jumps and running up and down stadium stairs. The compression, tension and shear tibial surface strains during standing vertical jumps were higher than strain levels previously reported during vigorous activity [9].

Discussion

This study was undertaken to better understand the etiology of the posteromedial tibial stress fracture. Tibial surface strain recordings in

Table 1
Principal strains in microstrain (με) during staircase jumps.

Number of steps	Compression με	Tension με	Shear με
1	−2340	2150	4490
2	−770	510	1280
3	−2050	1780	3830
4 [a] first landing stumble step	−199	1542	1741
	−1215	512	1727

[a] Landing from this jump involved an initial landing followed by a subsequent stumble forward before a stable position was achieved.