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Journal of Biomechanics 40 (2007) 845–850

JOURNAL OF BIOMECHANICS

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The effect of muscle fatigue on in vivo tibial strains

Charles Milgrom[a,*], Denitsa R. Radeva-Petrova[a], Aharon Finestone[b], Meir Nyska[c], Stephen Mendelson[d], Nisim Benjuya[e], Ariel Simkin[a], David Burr[f]

[a]Department of Orthopaedics, Hadassah University Hospital, Ein Kerem, P.O. Box 12000, Jerusalem, Israel
[b]Department of Orthopaedics, Israeli Defence Forces Medical Corps, Israel
[c]Meir Hospital, Kfar Saba, Israel
[d]Mendelson Orthopaedic Institute, Detroit, MI, USA
[e]Biomechanics Laboratory, Kaye College of Education, Beersheva, Israel
[f]Department of Anatomy and Orthopaedics, University of Indiana School of Medicine, Indianapolis, IN, USA

Accepted 12 March 2006

Abstract

Stress fracture is a common musculoskeletal problem affecting athletes and soldiers. Repetitive high bone strains and strain rates are considered to be its etiology. The strain level necessary to cause fatigue failure of bone ex vivo is higher than the strains recorded in humans during vigorous physical activity. We hypothesized that during fatiguing exercises, bone strains may increase and reach levels exceeding those measured in the non-fatigued state. To test this hypothesis, we measured in vivo tibial strains, the maximum gastrocnemius isokinetic torque and ground reaction forces in four subjects before and after two fatiguing levels of exercise: a 2 km run and a 30 km desert march. Strains were measured using strain-gauged staples inserted percutaneously in the medial aspect of their mid-tibial diaphysis. There was a decrease in the peak gastrocnemius isokinetic torque of all four subjects' post-march as compared to pre-run ($p = 0.0001$), indicating the presence of gastrocnemius muscle fatigue. Tension strains increased 26% post-run ($p = 0.002$, 95 % confidence interval (CI) and 29% post-march ($p = 0.0002$, 95% CI) as compared to the pre-run phase. Tension strain rates increased 13% post-run ($p = 0.001$, 95% CI) and 11% post-march ($p = 0.009$, 95% CI) and the compression strain rates increased 9% post-run ($p = 0.0004$, 95% CI) and 17% post-march ($p = 0.0001$, 95% CI). The fatigue state increases bone strains well above those recorded in rested individuals and may be a major factor in the stress fracture etiology.

Keywords: Muscle fatigue; Tibial bone strains; Stress fracture; In vivo; Human

1. Introduction

Stress fracture is a common musculoskeletal problem affecting athletes and soldiers. Repetitive high bone strains and strain rates are considered to be the etiology of stress fracture (Burr et al., 1996; Milgrom, 2001) either with or without the mediation of the bone remodeling response (Schaffler, 2001).

In vitro mechanical testing of bone has shown its high resistance to mechanical loading. In bench testing, cortical bone fails within 10^3–10^5 loading cycles at strain ranges of 5000–10000 με (Carter et al., 1981). When the strain level is lowered to 3000 με in uniaxial tension, bone fails at 10^6 cycles. At tensile strains of 1500 με, cortical bone does not fail in tension by fatigue even after 37 million loading cycles (Schaffler et al., 1990). In vivo measurements of human tibial strains from surface mounted strain gauges have shown that strains do not exceed 2000 με even during very vigorous physical activity (Burr et al., 1996).

A discrepancy exists between the results of laboratory bench studies and in vivo human bone strain recordings: the level of strains in vivo is lower than that considered necessary to cause bone fatigue failure in laboratory

*Corresponding author. Tel.: +972 50 7874401; fax: +972 2 6778052.
E-mail address: milgrom@md2.huji.ac.il (C. Milgrom).

0021-9290/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2006.03.006

studies. It has been found that most stress fractures in military recruit epidemiological studies take place between the fourth and eighth week of basic training. This is well before a sufficient number of loading cycles has occurred necessary to fatigue mechanically tested cortical bone.

One explanation for this discrepancy is that bone strain rates increase markedly during the muscular fatigue phase (Yoshikawa et al., 1994) and reach levels far above the level recorded in vivo from non-fatiguing exercise. To test this hypothesis, we measured in vivo human tibial strains and strain rates before and after fatiguing physical activities.

2. Methods

Four male members of the research staff (27–52 years of age) volunteered to be subjects for in vivo tibial strain measurements. All subjects received explanations of the goals, risks and benefits of their participation in the experiment and signed informed consent. The experimental protocol received the institutional review board approval. The subjects were healthy, with no prior history of medical problems.

2.1. Strain gauged staples (SGS)

In order to measure in vivo tibial bone strains and strain rates during exercises, instrumented bone staples were used. They were fabricated from an orthopedic 16×15 mm bone staple (3 M Health Care, St. Paul, Minnesota), with a Micro-Measurements EA-06-031DE-350 strain gauge (Measurements Group, Inc., Raleigh, NC, USA), bonded to the undersurface of the staple. The staple was wired as a 1/4 Wheatstone bridge. Three SGSs were inserted percutaneously in a 30° rosette pattern in the medial aspect of the mid-tibial diaphysis (Milgrom et al., 2000a).

2.2. Surgical technique

The percutaneous surgical implantation of a rosette of three SGSs was performed on an outpatient basis on each of the subjects under local anesthesia. Prophylactic intravenous cefonicide was given prior to surgery (Milgrom et al., 2000a).

To facilitate the accurate placement of the SGS rosette, a drill alignment jig was used. The jig was placed over the skin on the medial tibial border at the mid-tibial length. Surgical skin stab wounds were made corresponding to the jig pattern with the entrance holes of the central staple parallel to the long axis of the medial tibia and the two oblique staples 30° from this axis. The entrance sites were predrilled to a depth of 4 mm and the staples inserted with the use of a specially made inserter—impacter, which allows the staple to be driven into the predrilled hole to a depth of 4 mm within the cortex. After insertion, the gauges were checked by an ohm meter to see that no damage had occurred during insertion.

At the end of the experiment, after the completion of data collection, removal of the staples was performed in the orthopedic clinic.

2.3. Fatigue protocol and SGS measurements in vivo

The strain gauge exiting wires were connected to a portable four-channel amplifier. The conditioned amplifier signals were recorded on a FM analogue cassette recorder (TEAC HR10, TEAC Corp., Tokyo, Japan). Playback was by a separate unit (TEAC MR40, TEAC Corp.) connected to a PC and digitized at 400 Hz (Milgrom et al., 2000a).

Each subject performed the experiment on a separate day so that post-fatigue measurements could be made as soon as possible after completing activities. All subjects wore Nike Air Max shoes for the experiment which began at 8 am, after the strain gauges had been surgically implanted. Prior to beginning the fatigue protocol, subjects had already done 5 h of light exercise activities. These included serial 50 m over ground runs, basketball shooting and rebounding drills, standing broad jumps, vertical jumps, hopping, zig-zag hopping, treadmill walking and running, exercise bicycle sprints, leg squats with weights and step climbing. Subjects were then driven 2 h to a research laboratory in the desert for the fatigue protocol. Before the beginning of this protocol, baseline measurements were made as follows: the maximum right gastrocnemius isokinetic torque was measured using a Biodex isokinetic strength measuring station (Biodex Medical Systems, Shirley, New York, USA). While the subject was walking over a 12 m long walkway with an AMTI force plate (Advance Mechanical Technology, Inc., Watertown, Massachusetts) embedded in the center, tibial strains and strain rates as well as the ground reaction forces from the force plate were recorded.

When the baseline measurements were completed, the fatigue protocol started. All subjects ran 2 km at their own pace, but not less than 12 km/h. The repetition of the baseline measurements began 3 min after completing the run. The maximum gastrocnemius isokinetic torque measurement took less than 2 min to complete. The tibial strains and force plate measurements were made 1 min afterward.

After an hour rest, the subjects began a 30 km march. The march started early in the evening. It was over a hilly desert terrain and at a forced pace of 6 km/h. The temperature during the marching was in the range of 25–30 °C. After completion of the march, the baseline measurements were repeated. For the two subjects who

completed the march, the measurements began 3 min after completing the march. The two subjects who did not complete the march were driven from the point they stopped to a point 500 m from the laboratory. The drive took 3 min for the subject who completed 27 km and 7 min for the subject who completed 23 km. The subjects walked 500 m to the laboratory and the repetition of the baseline measurements began 3 min later.

2.4. Data analysis

Raw data from the axial SGS was processed using a custom-written computer program running under Windows, which takes the digitized amplified SGS signals, filters them at 5 Hz, performs baseline corrections and derives the maximum axial compression and tension strains and strain rates.

The fatigue protocol was divided into three data collection phases: baseline pre-run, post-run and post-march. The mean axial compression and tension strains and strain rates of all subjects while walking in the different phases were calculated. For each subject and each phase, these calculations were based on four steps. Data were analyzed using the Statistical Analysis System (SAS, Cary, NC, USA). Comparisons of the mean peak axial strains and strain rates before and after activities for all subjects were done by univariate repeated measures analysis of variance (ANOVA). Adjustment for multiple comparisons between means was done by the Tukey–Kramer method. Comparisons between pre-run, post-run and post-march values of peak gastrocnemius isokinetic torque and peak vertical ground reaction force were made using ANOVA.

3. Results

Two out of the four subjects completed the entire march (Table 1). One of the subjects halted the march at the 23rd kilometer and another at the 27th kilometer because of extreme muscle fatigue. Subjectively, the muscle fatigue was principally felt by subjects in the thigh and hip region. Diagonal strain gauge exiting wires broke in two of the subjects. The axial aligned gauges were intact in all subjects, so only their output was used for strain calculations.

There was a statistically significant decrease in the peak gastrocnemius isokinetic torque in the case of post-march as compared to pre-run (Table 1). For the two subjects who did not complete the march, the peak gastrocnemius torque post-march was reduced by 37% and 31% in comparison to pre-run levels. The reduction was 21% and 23% for the two subjects who completed the march.

Table 1
Peak gastrocnemius isokinetic torque and peak vertical ground reaction force of all subjects pre-run, post-run and post-march

Age	Gastrocnemius torque[a] (Nm)			Peak vertical force[b] (N)			March (km completed)
	Pre-run	Post-run	Post-march[c]	Pre-run	Post-run	Post-march	
27	113	102	71	1168	1158	1094	23
37	131	110	101	1071	1076	1050	30
45	124	126	98	1170	1116	1184	30
52	80	81	55	1241	1210	1002	27

[a]Measured by Biodex isokinetic dynamometer.
[b]Measured by AMTI force plate.
[c]Peak gastrocnemius isokinetic torque was significantly decreased in all subjects post-march in comparison to pre-run ($p = 0.0001$). No other statistically significant differences were detected between the phases.

Table 2
Mean tibial axial strains and strain rates of all subjects pre-run, post-run and post-march

Phase	Strains (με) (95% confidence limits)		Strain rates (με/s) (95% confidence limits)	
	Tension	Compression	Tension	Compression
Pre-run	394 (342–446)	672 (628–716)	4683 (4429–4937)	3820 (3687–3952)
Post-run	533 (481–585)	572 (528–616)	5391 (5138–5645)	4217 (4084–4349)
Post-march	558 (508–608)	513 (470–556)	5233 (4988–5477)	4615 (4488–4743)
P-value				
Pre-run vs. post-run	0.002	0.008	0.001	0.0004
Pre-run vs. post-march	0.0002	0.0001	0.009	0.0001
Post-run vs. post-march	0.766	0.14	0.633	0.0003

To compare the axial compression and tension strains and strain rates of the three phases of the fatigue protocol, the mean values of all subjects were used. There were statistically significant changes in all strains and strain rates post-run and post-march as compared to the pre-run phase (Table 2). When compared to the pre-run, the tension strains increased 26% post-run and 29% post-march, and the tension strain rates increased 13% post-run and 11% post-march. The compression strains decreased 15% post-run and 24% post-march, but the compression strain rates increased 9% post-run and 17% post-march. Compression strain rates also increased significantly (9%) post-march when compared to post-run.

4. Discussion

The most intensively studied model for stress fractures to date has been the Israeli infantry recruit (Finestone et al., 1999; Giladi et al., 1991; Margulies et al., 1986; Milgrom et al., 2000b 1989, 1985). When in vivo tibial strains were measured during activities that simulated the recruits' training, strains were found to be lower than those necessary to cause bone fatigue in laboratory ex vivo studies. The simulations were excerpts from activities of the soldiers' training schedule in a rested subject. They did not reflect the grueling nature of the training. None of the measurements were made after a 60 km march or during training for 48 h without sleep. We hypothesized that during fatiguing exercises, bone strains and strain rates reach levels well above those measured previously in vivo in the non-fatigue state. If the hypothesis is correct, then the fatigue state puts subjects at an increased risk for stress fracture.

In vivo tibial strain measurement is an invasive procedure and requires surgical implantation of strain gauges. Although it is done on healthy subjects, it involves risks, principally that of infection. Therefore, before doing in vivo strain measurements, we wanted to gather preliminary evidence to support the hypothesis that the fatigue state increases bone strains. Verbitsky et al. (1998) have previously found that muscle fatigue leads to a 50% increase in tibial accelerations during treadmill running. They assessed fatigue by respired gas exchange and ventilatory variables. They explained the increased accelerations by the inability of the fatigued muscles to control knee extension and flexion in a way that attenuates impact at heel strike (Verbitsky et al., 1998; Mizrahi et al., 2000a). Flynn et al. (2004) studied the effect of localized leg muscle fatigue on tibial impact acceleration. In their experiment, the unshod foot of subjects was repeatedly impacted into a vertical force plate using a human pendulum method, and electromyography (EMG) activity of the gastrocnemius and tibialis anterior muscles was monitored along with accelerations at the tibial tubercle. A significant decrease in peak tibial accelerations was found following muscle fatigue. In their experiment, the exercise performed was isometric and there was no general or whole body metabolic fatigue as in the Verbitsky and Mizrahi studies. As a preliminary to the present study, we decided to measure tibial accelerations, using the technique described by Voloshin and Wosk (1981). We measured the tibial accelerations at the level of the tubercle in 10 soldiers before and after a fast 24 km march with only a light pack and gun. For the Israeli infantry recruit this is considered to be a light march. The accelerations increased post-march by 13% (Finestone, 1990). With this support for the hypothesis, we decided to carry out a formal in vivo strain measurement study.

In this study two fatiguing levels of exercise were evaluated: a 2 km run and a forced paced 30 km desert march. Muscle fatigue was defined as the decreased ability of the muscles to perform work. Peak gastrocnemius torque measurements were used in the current experiment to assess muscle fatigue, with comparisons of pre- and post-performance on a Biodex isokinetic muscle testing machine. The measurements showed that the 2 km run did not produce a significant change in the peak gastrocnemius torque post-run. Post-march there was a significant decrease. No differences in the peak vertical ground reaction force were found. These measurements indicate that gastrocnemius muscle fatigue was present post-march but not post-run. Subjects reported mild muscle fatigue after their run. At the end of the march subjects were exhausted. They felt pronounced muscle fatigue, which was more extreme in the thigh and hip region. This region was not assessed for fatigue in the study. If muscle fatigue measurements had been made in this area, they may have shown more profound fatigue changes than those we measured in the gastrocnemius muscle.

The study fatigue protocol included baseline measurements of the maximum gastrocnemius torque, peak vertical force, strains and strain rates pre-run, post-run and post-march, but not pre-march. It is therefore impossible to determine what the changes were in relation to the immediate pre-march status. Subjects at the beginning of the march may have either recovered fully or partially to the pre-run baseline measurements at the start of the fatigue protocol. We therefore do not know if the observed strain changes at the end of the march were the result of the march only or the cumulative effect of the run and the march together. In either case, the results indicate that whole body fatigue affects tibial strains.

In vivo strain measurements were made using percutaneously applied instrumented bone staples. The advantage of this measurement technique is the less invasive nature of their surgical application compared to

surface mounted gauges. The technique is most useful in comparing relative axial intra-subject differences between activities and not absolute strains (Milgrom et al., 2004).

The present study supports the hypothesis that the fatigue state increases bone strains. The strain measurements were made during walking immediately post-run and post-march. Strain recordings were not attempted during the course of the actual exertional activities because of fear of strain gauge wire breakage. Even with this limitation, post-march tension strains increased by 29%, tension strain rates by 11% and compression strain rates by 17%. Compression strains were the exception and decreased. The strain increases in the fatigued subject when he pushes his body to the limit during running and marching while carrying a heavy pack may be even larger than those we recorded. The subjects in this experiment were much older than military recruits. What the bone strains are in young recruits in the same circumstances is not known.

In previous animal studies, muscle fatigue has often been identified as the cause for increase in bone in vivo strains and strain rates. Yoshikawa et al. (1994) found in a dog model that strains increased and the strain distribution pattern changed with muscle fatigue measured by EMG. Bone strains did not increase when muscles failed to become fatigued. Shear strains increased at a greater rate after muscle fatigue than did either principal tensile or compressive strains. Because we could only use output from the axial staple strain gauges in this experiment, we were unable to measure the change in shear strains. But based on these experimental data, we suggest that shear strains may increase even more greatly than the compressive and tensile strains we measured.

The magnitude of the changes following fatigue in canine studies is consistent with those found in human studies. In an in vivo human study, Fyhrie et al. (1998) measured the effect of a 10 min fatiguing treadmill run at a speed of 11 km/h on tibial axial strains using a percutaneous extensometer. A post-fatigue increase in axial strain rates was noted and found to be age dependent. Voloshin et al. (1998) measured the effect of fatigue on tibial accelerations in humans, using physiological criteria. For those who reached fatigue by the end of the fatigue protocol, there was a significant increase in the amplitude of the acceleration signal. No such increase occurred in the non-fatigued subjects.

Clinical observations indicate that stress fractures and other overuse injuries occur most often following muscle fatigue, or with an abrupt change in the normal training routine (Clement et al., 1981), when the capacity of muscles to protect bone from excessive overloads is compromised. Muscles dissipate dynamic forces generated in the skeleton by eccentric contraction (Hill, 1960; Radin et al., 1986). They reduce strain rate by absorbing impact energy during movement. Force transients of 5–10 g are produced at heel strike (Light et al., 1980). The leg muscles decelerate the limb before heel-strike (Inman et al., 1981) and attenuate potentially large ground reaction forces (Mizrahi and Susak, 1982; Mizrahi et al., 2001, 2000b; Radin et al., 1986). The time for this reflexive energy dissipating action of muscles is quick, between 75 and 100 μs (Nyland et al., 1994). Altered neuromuscular function, often occurring with muscle fatigue, may slow muscle reaction or otherwise prevent this normal damping mechanism (Mizrahi et al., 2001). The transfer of mechanical energy between the eccentric and concentric phases of muscle contraction is reduced during muscle fatigue (Gollhofer et al., 1987; Mizrahi et al., 2000b, c, 2001), making the muscle less capable of dissipating impact energy. This may be exacerbated during downhill running (Mizrahi et al., 2000b) as fatigue of the quadriceps will allow increased vertical excursion of the hips (Mizrahi et al., 2001) and attenuated shock absorption, leading to higher tibial bending stresses (Mizrahi et al., 2000c).

We conclude from this experiment that training in the fatigued state may be a major factor contributing to the high stress fracture rate in Israeli infantry recruits (Milgrom et al., 1985). The fatigue state increases the bone strains well above those recorded in rested individuals participating in laboratory experiments.

Acknowledgment

This work was supported by Hadassah University Hospital research fund 513.009.

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