ESTIMATION OF STRESSES AND CYCLES TO FAILURE OF THE TIBIA DURING RESTED AND FATIGUED RUNNING

[1]Siriporn Sasimontonkul, [2]Brian K. Bay, and [1]Michael J. Pavol
[1]Department of Exercise & Sport Science; [2]Department of Mechanical Engineering
Oregon State University, Corvallis, OR, U.S.A.
Email: fedusrs@ku.ac.th

INTRODUCTION

Many runners suffer from tibial stress fractures. This may be a result of the repetitive loading applied to the tibia during running, as there is evidence of micro-damage in bone tissue after repetitive loading. Therefore, this study investigated 1) whether running-related loads are large enough to cause tibial stress fractures upon repeated application, and 2) whether muscle fatigue alters the potential for tibial stress fractures during running. The potential for tibial stress fractures was predicted, using an integrated experimental and mathematical modeling approach, by estimating the minimum number of loading cycles that would result in the failure of bone (Nfail).

METHODS

Ten male recreational runners with reflective markers attached to their left lower limb ran across a force plate for a total of 6 successful trials within the range of 3.5 – 4 m/s. Subjects then ran on a treadmill until muscle fatigue occurred, as indicated by a decrease of >25% in measured plantarflexion strength. Finally, the fatigued subjects performed 6 more running trials across the force plate within the same range of 3.5 – 4 m/s.

Inverse dynamics analysis was applied to the marker position and force data to estimate the joint reaction forces (JRF) and joint moments at the left ankle, knee, and hip. The forces acting in 21 muscles of the lower limb at each sample time were estimated from the joint moments through optimization, minimizing the sum of the cubed muscle stresses. From the JRF and the muscle forces, the 2-D bone contact forces at the distal end of tibia were computed. Stresses on the anterior and posterior faces of the tibia at 13.7 cm. from the distal end were then estimated from the bone contact forces, based on a beam model [1]. Finally, the tibial stresses were used to predict Nfail [2]. Nfail was log transformed for statistical analysis and a doubly multivariate was used to compare Ln(Nfail) before and after the onset of muscle fatigue.

RESULTS AND DISCUSSION

Compressive stresses were found at the posterior face of the tibia throughout stance, whereas both tensile and compressive stresses acted at the anterior face (Figure 1). This is consistent with strains that have been measured *in vivo* and *in vitro* [3,4]. The maximum compressive stress of -43.4 ± 10.3 MPa occurred at the posterior face of the tibia during mid stance and resulted in the minimum Nfail. Hence, the posterior face of the tibia was more prone to stress fractures, consistent with the results of a previous epidemiological study [5]. Although Nfail before fatigue averaged 5.28×10^6 cycles, Nfail varied greatly between runners. The mean Nfails of two runners were only 2.7×10^4 and 2.7×10^5 cycles, suggesting that these two runners were at risk of a tibial stress fracture from running.

After muscle fatigue, tibial stresses tended to decrease (Figure 1), which led to a significant increase in Nfail (Table 1). This increase in Nfail implies that fatigue of the plantarflexors from prolonged running did not accelerate the onset of tibial stress fractures. Instead, changes in running technique with fatigue may have served to protect against tibial stress fracture. The results thus indicate that tibial stress fractures in runners result primarily from the repeated application of running-related loads in selected, at-risk individuals, and not from an increase in bone loading due to muscle fatigue.

Table 1: The group mean ± SD of Ln(Nfail) and the mean of Nfail at the posterior and anterior faces of the tibia.

	Before fatigue	After fatigue	P-value
Ln(Nfail)			
Posterior face	15.48 ± 2.56	16.07 ± 2.44	0.004
Anterior face	27.00 ± 4.95	27.94 ± 4.01	0.095
Nfail (cycles)			
Posterior face	5.28×10^{6}	9.53×10^{6}	–
Anterior face	5.32×10^{11}	1.36×10^{12}	–

REFERENCES

1. Sasimontonkul S. *Dissertation*, 2004.
2. Caler WE, et al. *J. Biomech*, **22**, 625-35, 1989.
3. Ekenman I, et al. *Foot Ankle Int.*, **19**, 479-484, 1998.
4. Peterman MM, et al. *J. Biomech*, **34**, 693-8, 2001.
5. Brukner P, et al. *Phys Sportsmed*, **26**, 39-47, 1998.

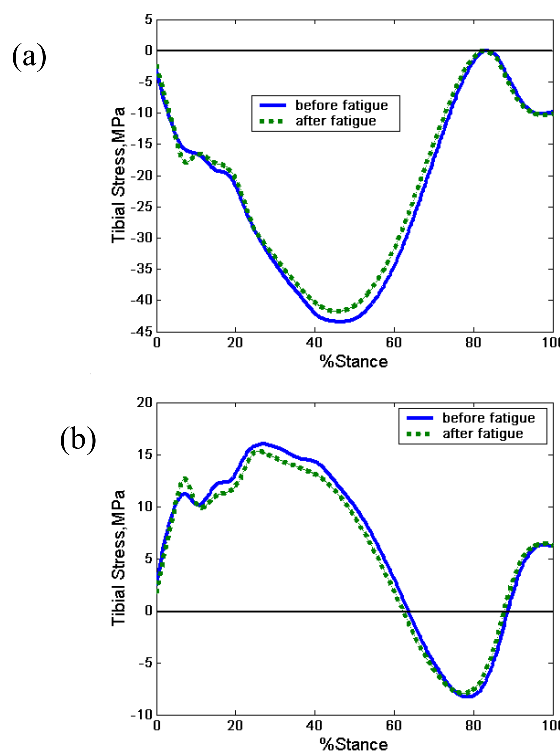

Figure 1: Mean stresses before and after muscle fatigue at the (a) posterior and (b) anterior faces of the tibia during the stance phase of running. Positive stresses are tensile and negative stresses are compressive.