THE PROBABILITY FOR TIBIAL STRESS FRACTURE INCREASES WITH RUNNING SPEED DESPITE A REDUCTION IN THE NUMBER OF LOADING CYCLES

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Introduction

Stress fractures are common overuse injuries among runners that result from the mechanical fatigue of bone. The failure of materials subjected to mechanical fatigue is dependent on both loading magnitude and loading exposure. Reducing speed is one potential mechanism of load reduction during running [1]. However, a reduction in running speed is associated with an increased number of loading cycles for a given mileage (assuming a positive relationship between stride length and speed). It is therefore unclear if these increased loading cycles are detrimental to skeletal health despite reductions in loading magnitude.

The purpose of this study was to determine the influence of running speed on the probability of tibial stress fracture. We hypothesized that reducing running speed would decrease tibial strain sufficiently enough to negate the detrimental increase in loading cycles associated with a given running mileage. This would lead to a reduction in the probability of tibial stress fracture with a corresponding decrease in running speed.

Methods

Ten male subjects ran overground at three prescribed speeds (2.5, 3.5, and 4.5 m/s). Force platform (1600 Hz) and kinematic data (160 Hz) were collected synchronously. Average stride frequency was recorded. Cardan joint and segment angles were calculated. Joint moments and reaction forces were determined for the hip, knee, ankle, and subtalar joint using standard inverse dynamics. A SIMM musculoskeletal model, containing 43 lower-extremity muscles, was used to obtain maximum dynamic muscle forces (adjusted for muscle length and velocity), muscle moment arms, and muscle orientations. This information was used in a static optimization routine to estimate individual muscle forces during stance. The cost function to be minimized was the sum of squared muscle stresses. Six moments were used to constrain the optimization including the three orthogonal components at the hip, the flexion-extension moment at the knee and ankle, and the subtalar moment. Contact forces acting on the distal tibia were calculated as 90% the vector sum of the ankle reaction force and muscle forces crossing the ankle joint (the fibula bears 10% of the load) [2]. Peak instantaneous contact force served as input to a finite element model to estimate tibial strains during stance. A separate model was created for each subject that was scaled to the individual’s leg length.

Stress fracture probability at each speed was determined using a probabilistic model of bone damage, repair, and adaptation [3]. The stress fracture model used the Weibull approach, a common procedure in fatigue mechanics used to determine the probability of failure when there is considerable scatter in a material’s fatigue behavior (e.g., cortical bone). The model began with a modified Weibull equation that accounted for stressed volume:

\[ P_f = 1 - \exp\left[-\frac{V_s}{V_{so}}\left(\frac{t}{t_f}\right)^w\right] \]

where \( V_{so} \) is the reference stressed volume, \( t_f \) is the reference time until failure at the applied strain level and number of loading cycles/day, and \( w \) expresses the degree of scatter in the material. These constants were derived from experimental fatigue testing literature and allowed the researcher to predict the cumulative probability of failure \( P_f \) for a specimen having stressed volume \( V_s \) from time zero to \( t \). Bone repair was incorporated into the model with a second Weibull equation:

\[ P_r = 1 - \exp\left[-\left(\frac{t}{t_r}\right)^v\right] \]
where \( t_r \) is the reference time until repair and \( \nu \) expresses the degree of scatter in repair (i.e., variability in the time for a basic multicellular unit to tunnel through and remove a microcrack). By determining the probability that bone will not repair itself \((1-P_f)\) and multiplying it by the instantaneous probability that failure will take place \((\text{time differential of } P_f)\), we obtained an instantaneous probability that accounted for failure and repair; integrating with respect to time gave the cumulative probability of failure with repair \((P_{fr})\). For adaptation, we assumed a rate of 4 \( \mu \)m/day of bone deposition on the periosteal surface. Standard beam theory was then used to determine the change in strain over time \( t \). This change in strain was converted to a single equivalent strain using a weighted average procedure. The equivalent strain was utilized within the “failure” Weibull equation \( P_f \) to determine the probability of failure with repair and adaptation \((P_{fra})\).

Cumulative \( P_{fra} \) was determined for a running regimen of 3 miles/day over the course of 100 days. Differences in peak \( P_{fra} \) as a function of running speed were compared using a repeated measures ANOVA \((\alpha=0.05)\) with Bonferroni adjusted post-hoc comparisons \((\alpha=0.05/3=0.017)\).

**Results**

Peak \( P_{fra} \) occurred after approximately 40 days of training (Fig. 1). Decreasing running speed from 4.5 to 3.5 m/s reduced the likelihood for tibial stress fracture by 4% \((p=0.01; \text{ Table 1})\). Decreasing running speed from 3.5 to 2.5 m/s reduced the likelihood for tibial stress fracture by 12% \((p=0.01)\).

**Table 1.** Mean peak \( P_{fra} \) (SD) across running speeds. Significant differences were observed between all speeds \((p<0.017)\).

<table>
<thead>
<tr>
<th>Speed</th>
<th>( P_{fra} ) (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 m/s</td>
<td>0.17 (0.21)</td>
</tr>
<tr>
<td>3.5 m/s</td>
<td>0.29 (0.29)</td>
</tr>
<tr>
<td>4.5 m/s</td>
<td>0.33 (0.30)</td>
</tr>
</tbody>
</table>

**Discussion**

The purpose of this study was to determine the effects of running speed on the probability of tibial stress fracture. Our hypothesis was supported by the results of this study in that a linear reduction in running speed resulted in a corresponding non-linear reduction in peak \( P_{fra} \). Therefore, runners wanting to reduce their probability for tibial stress fracture may benefit from a decrease in running speed. This finding was a direct result of the reduced joint contact forces and therefore reduced strains associated with slower running speeds. Because a reduction in running speed was also associated with an increase in the number of loading cycles for a given running mileage, it appears that stress fracture development is more dependent on loading magnitude rather than loading exposure. This statement is of course specific to the parameters investigated in this study and may therefore not apply to different running velocities and mileages.

**Conclusions**

For a given mileage, a decrease in running speed reduces the likelihood for tibial stress fracture. Strain magnitude may play a more important role in stress fracture development than the total number of loading cycles.

**References**