Quantifying Athletic Stress Fracture Bone Metrics: Insights from CT Imaging and Finite Element Analysis

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Introduction: Stress fractures in athletes are the result of cumulative sub-maximal mechanical trauma to bone tissue, which manifests as a gradual onset of pain and increases the risk of progressing to a complete fracture, thereby compromising athletic performance [1]. In the context of sports-related injuries among U.S. high school athletes, it is estimated that the incidence rate of stress fractures is 1.54 per 100,000, with the tibia and fibula being the most affected bones [2]. Often, affected athletes report a recent escalation in the intensity of their training regimen prior to experiencing symptoms [1]. While magnetic resonance imaging (MRI) serves as the diagnostic gold standard for stress fractures not visible on conventional X-ray imaging [3], recent advancements in radiology have seen the increased application of computed tomography (CT) scans for diagnosing a variety of conditions, such as fatty liver, pulmonary nodules, bile duct lesions, and meningiomas. This is largely due to CT scans' ability to quantify tissue density via the Hounsfield unit (HU) [4]. Recent advancements in CT technology have also facilitated high-resolution imaging of tibial stress fractures in clinical settings, leading to the utilization of finite element analysis (FEA) for examining the biomechanical properties of diseased bone [1]. In our study, we utilized both CT scanning technology and FEA modeling to examine stress fractures. Using CT scans, we quantified the HU of athletic stress fractures and compared these to the HU values of normal bone within the same individual. Simultaneously, we utilized FEA to test the hypothesis that the stiffness of stress fractures, as measured in kN/mm, is lower than that of normal bone in the same individual and anatomical location.

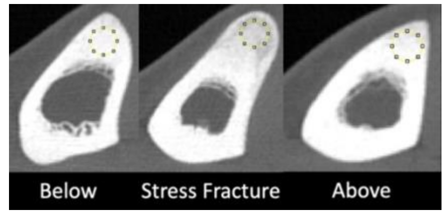

Figure 1: Representative images of CT scans of the tibia of a patient with a stress fracture. In yellow, ROIs of the stress fracture, above and below it.

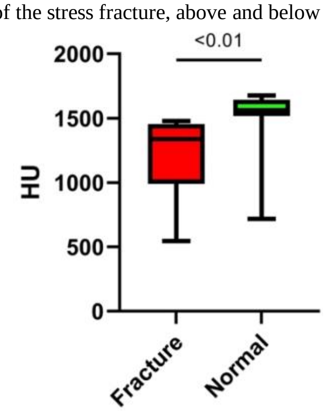

Figure 2: Box and Whiskers plot showing the difference between the HU values of stress fractures and normal bone.

Methods: We examined 10 tibial CT scans from nine patients diagnosed with anterior/posteromedial tibial stress fractures (Figure 1), including one patient with bilateral stress fractures. The study population comprised six males and four females with a mean age of 34 ± 18. Each CT scan was individually analyzed using Sectra MSK (Version 24.2.6.5829). In-house software was used to segment fracture regions. To simulate "pre-fracture" bone, we modified the 3D models by virtually filling the fracture region with normal cortical bone HU values derived from neighboring regions without fractures. We then employed FEA to model the tibia and simulate compression along the bone's axial direction, as described by Rajapakse et al. (2).

Results: Our findings revealed a 2.5% [0.797% - 4.24%] decrease in bone stiffness in stress fracture patients compared to the pre-fracture baseline (Table 1). HU analysis demonstrated that stress fractures have significantly lower HU values than normal bone, with a mean difference of 300 HU and a P-value of < 0.001 (Figure 2) as the bone of a stress fracture heals and returns to its normal state, both HU and stiffness increase until they reach values indicative of normal bone.

Stiffness Before Fracture (kN/mm)	Stiffness with Fracture (kN/mm)	% Change
15.7282	15.2687	- 2.9
10.8762	9.9825	- 8.2
1.1178	1.0644	- 4.8
2.9460	2.9114	- 1.2
2.1031	2.0904	- 0.6
2.9743	2.9554	- 0.6
3.0181	2.9238	- 3.1
2.4628	2.4408	- 0.9
1.4631	1.4477	- 1.1
0.4086	0.4012	- 1.8

Table1. representing the % change in stiffness (kN/mm) in the tibias before and during the stress fracture injury.

Discussion Our study found that the HU in the ROIs surrounding the stress fractures was significantly lower than those in adjacent regions both above and below the fracture site within individual patients. Furthermore, using FEA modeling, we quantified the stiffness of bone both prior to and following the onset of stress fractures. We found that the development of a stress fracture is associated with a notable decrease in cortical bone stiffness. These metrics offer valuable criteria for assessing an athlete's readiness to return to competitive activities while minimizing the risk of further complications. In addition, these measurements furnish important insights into an individual's overall bone health and the progression toward full recovery of bone strength.

Significance/Clinical Relevance: Imaging has long been used for qualitatively diagnosing diseases with a disregard for its quantitative power. FEA modeling in suspected or current stress fractures can help us predict the risks of developing complete fractures and accelerate the return to play durations, hence reducing the costs caused by these injuries and improving overall athletic performances.

References:

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