

ANISOTROPIC STRESS ANALYSIS OF THE SECOND METATARSAL DURING THE STANCE PHASE OF GAIT

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INTRODUCTION

The second metatarsal (2nd Met) is a common site for stress fracture among athletes and military recruits. Although the exact cause of stress fractures remains unclear, it is believed to result from repetitive, cyclical loading. Understanding the loading environment at the 2nd Met may help to elucidate the etiology and aid in the prevention of stress fractures at this site.

In locomotion, peak longitudinal bone strain at the 2nd Met occurs during late stance, and tends to coincide with peak Achilles tendon force (Donahue et al., 2000). During this phase, the stresses acting along the principal material axes (Figure 1) of the 2nd Met are important, because models of stress fracture damage, repair and adaptation are based on stresses occurring in these directions (Taylor et al., 2004).

The purpose of this study was to: (a) quantify the stresses acting along the principal material axes of the 2nd Met during the stance phase of gait, (b) and determine the relationship between longitudinal stress and Achilles tendon force.

METHODS

Four fresh cadaver foot specimens were utilized for this study. A stacked rosette strain gage was mounted to the dorsal surface of the 2nd Met, and an intra-medullary rod was used to connect the tibia to a dynamic gait simulator.

The dynamic gait simulator is capable of simulating the stance phase of walking in approximately 1.0 sec and can replicate human ground reaction forces. Eight extrinsic muscles crossing the ankle joint are connected to load cells in series with motors to simulate muscle activity.

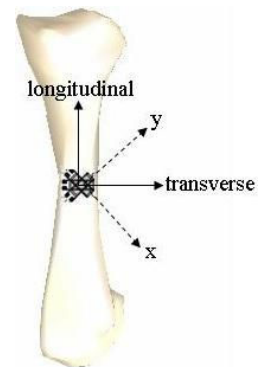


Figure 1: Principal material axes (trans-long) and rosette axes (x-y).

Each cadaver foot was outfitted with a sandal, and walked multiple trials across a force platform. Ground reaction force, bone strain, and muscle force data were collected concurrently at 1200 Hz. The data were exported to Matlab 7.0.4., and smoothed using a low-pass Butterworth filter with a cutoff frequency of 30 Hz. An anisotropic stress analysis of the strain rosette information during the stance phase of gait was then performed in accordance with Carter (1978). The principal strains and axes of orientation were calculated and rotated into the principal material directions. The stresses in the principal material directions were then calculated using material constants provided by Reilly and Burstein (1975).

The mean and standard deviation for peak longitudinal stress (σ_{long}), transverse stress (σ_{tran}), and shear stress (τ) were calculated

for each specimen. To determine the relationship between σ_{long} and Achilles tendon force (F_{at}) during stance, a cross-correlation at zero-lag was used. The mean correlation for all trials was calculated by converting the correlations to z-scores, calculating the average, and converting back to the correlation scale.

RESULTS AND DISCUSSION

A substantial amount of compressive σ_{long} was observed during the later portions of stance, while the σ_{tran} and τ appeared to be negligible in comparison (Figure 2). The mean peak σ_{long} for each specimen ranged between 11.18 MPa and 30.54 MPa (Table 1), and tended to occur near 70% of stance.

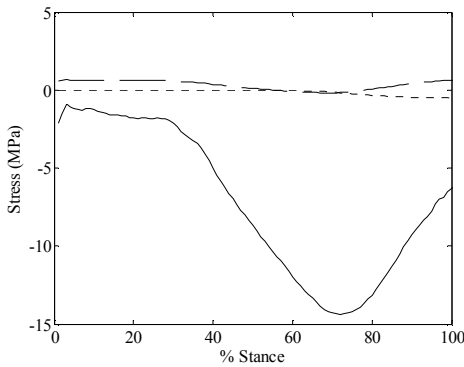


Figure 2: Principal material stresses for one representative trial. Solid line = σ_{long} ; Dashed line = σ_{tran} ; Dotted line = τ .

A strong cross-correlation was observed between σ_{long} and F_{at} (Figure 3). The correlation ranged from -0.85 to -0.99, with a mean of -0.97. The large correlation suggested that the σ_{long} was highly dependent on the plantarflexor moment that occurred during late stance.

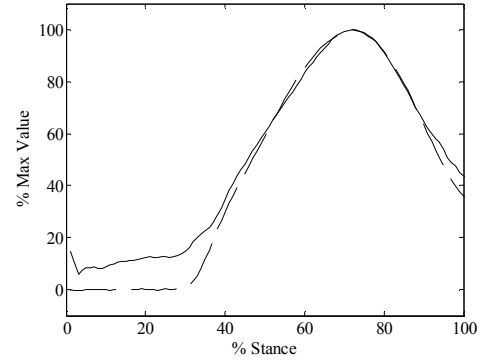


Figure 3: Relationship between σ_{long} and F_{at} for one representative trial. Solid line = $|\sigma_{\text{long}}|$; Dashed line = F_{at} .

SUMMARY/CONCLUSIONS

According to our model, the primary mode of loading on the dorsal 2nd Met during walking is compressive σ_{long} with little σ_{tran} . The small τ also suggested negligible torsional loading, although this may be due to the restricted tibial rotation in our model. The compressive σ_{long} is most likely due to bending caused by late stance plantarflexion. Stress fracture intervention should look to decrease this large bending stress, possibly with the use of orthotics.

REFERENCES

- Donahue, S. W. et al. (2000). *Bone*, **27**(6), 827-833.
 Taylor, D. et al. (2004). *J. Orthop. Res.*, **22**, 487-494.
 Carter, D. R. (1978). *J. Biomech.*, **11**, 199-202.
 Reilly, D. T. & Burstein, A. H. (1975). *J. Biomech.*, **8**, 393-405.

Table 1: Mean (1SD) peak stresses in principal material directions for the four specimens.

	Foot 1	Foot 2	Foot 3	Foot 4
σ_{long} (MPa)	30.54 (6.53)	18.17 (2.07)	11.34 (1.31)	11.18 (3.23)
σ_{trans} (MPa)	0.47 (0.13)	0.77 (0.10)	0.53 (0.04)	0.40 (0.08)
τ (MPa)	0.39 (0.17)	0.53 (0.22)	0.10 (0.04)	0.22 (0.07)