Maximum stresses in the human femoral diaphysis during walking

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Summary

Bone architecture is influenced by the dynamic loads resulting from locomotion [1]. During walking, the femoral diaphysis undergoes bending and torsional deformations, resulting in both tensile and compressive stresses. The maximum stresses occur on the medial aspect of the femur and increase proximally while the minimum stresses occur in the anterior-lateral quadrants of the middle-diaphysis.

Introduction

Mechanical loading (both mode and magnitude) influences bone remodeling, including the formation of the cortical pore network [2,3]. Understanding the contribution of porosity to bone strength is limited by the incomplete characterization of the habitual stresses of bone during locomotion [4, 5, 6]. Thus, the purpose of this study was to quantify the macroscopic and tissue-scale stress state of the femoral diaphysis during walking.

Methods

The principal stresses in the femoral diaphysis during walking were analysed using previously developed [7], subject-specific, muscle-driven finite element models (n=18) (Abaqus 2024). The models were co-registered using the linea aspera in the mid-diaphysis and divided into 5 sections (s1-s5, Figure 1A). The absolute maximum stress during the gait cycle was extracted for each cortical bone element. The orientation of the neutral axis (NA) was measured with respect to the medial-lateral axis. Each section was divided into 360 radial segments to measure the average stress.

NA data were normally distributed (Shapiro-Wilk) and analysed using one-way repeated measures ANOVA followed by a post-hoc analysis with a paired t-test and Bonferroni correction. Stresses were not normal (D'Agostino-Pearson K2), and compared using Statistical non-Parametric Mapping (spm1d v.0.4.18) with one-way ANOVA [8]. Post-hoc analysis: two-sample t-test and Bonferroni correction.

Results and Discussion

The maximum stresses in the diaphysis tended to occur at the time of the maximum ground reaction force (GRF). The overall stress state of the femur during walking was a combination of S-shaped bending (frontal) and torsion (sagittal, Figure 1A). In s1-s4, the lateral aspect was in tension while in the distal diaphysis (s5) tensile stresses were medial (Figure 1B). The s1 NA is in the anterior-posterior direction. Between s1-s4, the NA rotates laterally. The region between s4-s5 indicate the inflection point of bending with the NA translating medially and a reversal of loading mode (Figure 1C). There was no difference in the maximum compressive stress in the anterior and posterior regions. The stress state of the most proximal region of the diaphysis (s1-s2) was not different, however the stress state decreased at the mid-diaphysis (s3) and progressively decreased moving distally within each radial cross-section (s4, s5).

Conclusions

While torsion does occur within the femoral diaphysis, the predominant loading condition during walking is bending. The maximum stresses during walking vary spatially with the greatest tensile and compressive stresses occurring in the proximal diaphysis.

References

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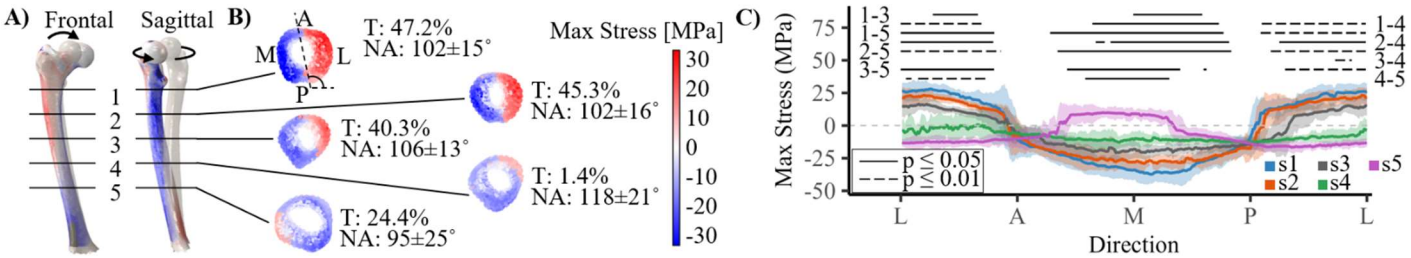

Figure 1: (A) Representative subject (rep.) second GRF peak stresses. Displacement magnified 15x. **(B)** Rep. max stresses. **(C)** SnPM max stresses.