

Maximum Stresses In The Femoral Diaphysis During Habitual Ambulation

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INTRODUCTION: Habitual mechanical loading (both mode and magnitude) influences bone remodeling processes at multiple length scales. Yet, a quantitative assessment of the mechanical stress state of cortical bone during locomotion remains^{1,2,3}. Understanding how bone is loaded during normative locomotive conditions has implications for pathologies that affect bone including atypical femur fractures, osseointegration of implants, and osteoporotic related impairments in bone quality^{4,5}. Thus, the purpose of this study was to compare the macroscopic and tissue-scale stress state of the femoral diaphysis during walking (w), stair ascent (sa), and stair descent (sd). We hypothesized that the stress state for different locomotive patterns is unique.

METHODS: The principal stresses in the femoral diaphysis were analysed using previously developed⁶, subject-specific, muscle-driven finite element models of postmenopausal women (w: n=18; sa/sd: n=17) due to the increased prevalence of osteoporotic fractures in women (Abaqus 2024). The model displacements were scaled to 15 times magnification, and the extremes were visualized in the frontal and sagittal views. The models were co-registered using the linea aspera in the mid-diaphysis, and sections in the proximal, middle, and distal diaphysis were selected. The absolute maximum stress during the gait cycle was extracted for each cortical bone element. Each cross-section was divided into 360 radial segments to measure the average stress. Stresses were not normal (D'Agostino-Pearson K2) and compared using Statistical non-Parametric Mapping (spm1d v.0.4.18) with one-way ANOVA⁷. Post-hoc analysis: two-sample t-test and Bonferroni correction.

RESULTS: All three locomotions had similar stress states throughout the stance phase. During early stance, the femur was under lateral S-shaped bending (frontal), posterior cantilever bending (sagittal), and torsion (sagittal), while late stance resulted in medial S-shaped bending, coronally aligned with the femoral axis. The deformations during walking (Fig 1A) were oriented medially while stair ascent (Fig 1B) resulted in lateral bending. Among the locomotive tasks, displacements during stair descent (Fig 1C) were the lowest. In the sagittal view, bending during walking occurred posteriorly, with a small degree of positive torsion while the mechanics of stair ascent had occurred with opposing magnitudes. Stair descent, on the other hand, was under less bending and more torsion occurring negatively and then positively during early and late stance, respectively.

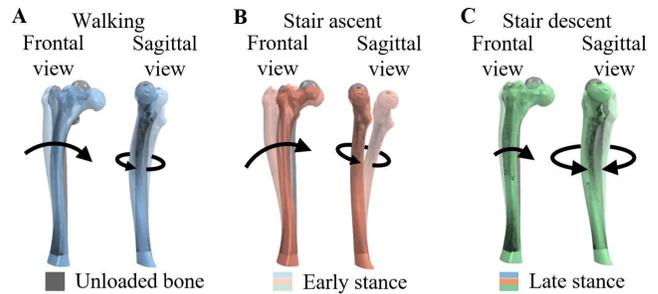


Figure 1. Representative subject's general stress state during early and late stance for (A) walking, (B) stair ascent, and (C) stair descent.

The stress distribution for all three locomotions followed the same general trend within each region. The proximal region (Fig 2A) neutral axis was along the anterior-posterior direction with tension on the lateral aspect. The mid region (Fig 2B) neutral axis was through the anterior-posterolateral direction with tension on the anterolateral aspect. The distal region (Fig 2C) reversed directions due to the S-shaped bending, such that the neutral axis was approximately through the anterolateral-posteromedial direction with tension on the anteromedial aspect. The proximal and distal regions were different, while the mid diaphysis region was not different between locomotions. In the proximal region, stair ascent was different from walking and stair descent in the anterolateral and posteromedial directions, and in the distal region, stair ascent was only different from stair descent in the anterior and anterolateral directions.

DISCUSSION: While the magnified displacements were different (Fig 1), the resulting stress patterns were overall similar in each locomotion with a few key differences. The significant regions were areas of different magnitudes and locations of the neutral axis. These results showed that stair ascent was different walking and stair descent, and walking had no differences from stair descent. Walking and stair descent locomotion is a controlled series of forwards falling and recovery, whereas stair ascent requires an individual to push themselves up to the next step. This difference in locomotive style could account for the difference in neutral axis location between stair ascent and the other two tasks. The push involved with stair ascent during early stance may explain the larger stair up displacement compared to the walking and stair descent. Our results differ from that of the femoral neck⁶. Walking resulted in more variable strains in the femoral neck, likely due to the difference in muscle insertions in addition to the overall difference in geometry analyzed. Future work should investigate whether these results hold true for men.

SIGNIFICANCE/CLINICAL RELEVANCE: This work has the potential to provide relevance to many clinical applications requiring understanding locomotive patterns⁸ and provides a comparison for assessment of the effect of disease.

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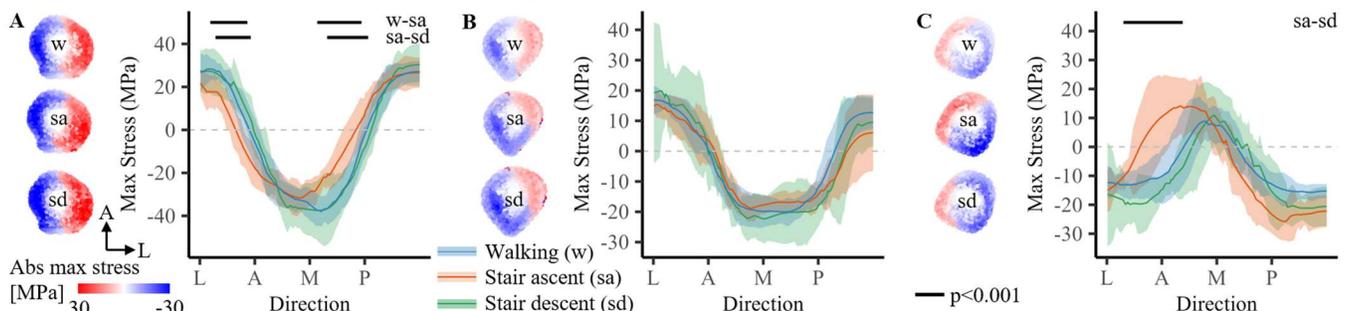


Figure 2. Representative subject's (A) proximal, (B) middle, and (C) distal diaphyseal cross-section and SnPM comparison of maximum stresses.