Biomechanical Stress Differences during Walking in Transtibial and Transfemoral Bone-Anchored Limbs: Implications for Stability

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INTRODUCTION: Bone-anchored limbs (BALs) are alternatives to traditional socket-based prostheses that anchor the prosthetic directly to the residual limb via a skeletally integrated implant [1]. However, some patients continue to experience mechanical complications, such as implant subsidence or periprosthetic fracture [2,3]. These failures often result from improper loading, with excessive loading (particularly before successful osseointegration) causing fracture and underloading leading to stress shielding and bone resorption/of aseptic loosening. Achieving a balance of stress at the bone-implant interface is critical for long-term success [4]. However, current methods for assessing *in-vivo* stresses are limited. Invasive strain gauges provide only localized data, and existing finite element analysis (FEA) models lack the subject-specificity needed to account for individual movement patterns and loading conditions [5]. In this study, we applied a novel and comprehensive FEA methodology [6] to estimate dynamic residual limb and bone-implant interface stresses during overground walking while incorporating subject-specific factors such as movement patterns, muscle forces, joint loads, and bone geometry.

METHODS: Motion capture data were collected from ten individuals with transfemoral (TF) BALs and six individuals with transtibial (TT) BALs (TF: age = 51.3 ± 10.8 yrs, BMI = 25.8 ± 3.8 kg/m^2, TT: = 45.2 ± 14.4 yrs, BMI = 27.3 ± 4.2 kg/m^2) during overground walking at self-selected speeds (TF: 0.98 ± 0.15 m/s, TT: 1.14 ± 0.23 m/s) using 38 reflective markers and six force plates to record kinematics and ground reaction force. Subject-specific musculoskeletal models were built using established methods [7,8] to analyze movement patterns, muscle forces, and joint loading. Computed tomography scans of the residual limbs were obtained prior to implantation to generate three-dimensional geometries of the residual limb, and implant geometries were reconstructed from postoperative radiographs. Residual limb models were meshed using tetrahedral elements, and the bone-implant interface was modeled as a bonded connection. A series of FEA on the residual limb were performed by updating muscle and joint forces throughout the gait cycle. FE simulations were conducted in Abaqus, with stresses analyzed in anatomically relevant regions (e.g., diaphysis and epiphysis). Peak stresses within each region were determined within each functional phase of gait and compared between the groups using a Cohen's *d* analysis.

RESULTS: Peak implant stresses were smaller for TF users than BAL users during terminal stance (46.0 ± 14.0 MPa vs. 85.3 ± 30.1 MPa, *d*=1.41) (Fig. 1). Contrarily, the peak stresses of the surrounding bone were similar across groups (TT diaphyseal = 42.2 MPa, TF femoral shaft = 42.8 MPa, *d*=0.08) (Fig. 1).

DISCUSSION: This subject-specific study estimated dynamic bone-implant loading in TF and TT BAL users during walking. Our results demonstrated that TT models exhibited similar diaphyseal stresses to TF models, but higher average implant stresses compared to TF patients. This may be because of smaller distal limb bone volume and increased lower limb reliance for body weight support, suggesting greater risks of implant subsidence, stress shielding, and long-term failure of the bone-implant interface. Conversely, TF models showed more balanced and slightly higher overall bone stresses when compared to implant stresses, potentially promoting bone remodeling but potentially increasing the risk of microdamage accumulation. These results may support early evidence suggesting higher mechanical failure rates in TT BAL users compared to TF
Future studies will explore the evolution and impact of mechanical differences on long-term implant success. These results suggest that stress patterns and magnitudes differ between TF and TT BALs, providing insight into implant loading strategies, ultimately enhancing clinical decision-making and implant success predictions.

SIGNIFICANCE/CLINICAL RELEVANCE: By capturing dynamic stress patterns that incorporate an individual's movement patterns, muscle forces, and joint loads, our findings emphasize the potential for more precise prediction of BAL success and stability. This subject-specific modeling approach offers valuable insight into how amputation level and patient-specific biomechanical properties affect in-vivo stresses. These results suggest that TT implants are at a greater risk of stress overloading at the implant, which could lead to short- and long-term mechanical complications.

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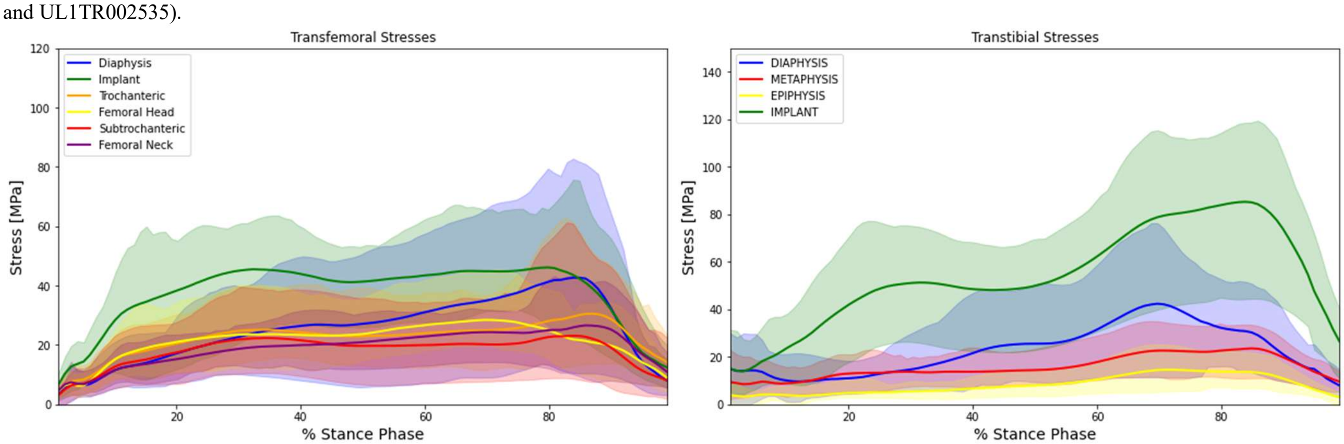

Figure 1: Mean stresses at the residual limb and BAL implant in transfemoral (left) and transtibial (right) bone-anchored limbs. Shaded regions represent the 10th to 90th percentiles of the mean.