

# Patient-Specific Determinants of Residual Limb Stresses in Transfemoral Bone-Anchored Limb Users

Jake Tinsley<sup>1</sup>, R. Dana Carpenter<sup>1</sup>, Jason Stoneback<sup>2</sup>, Brecca Gaffney<sup>1,2</sup>  
<sup>1</sup>University of Colorado Denver, Denver, CO  
<sup>2</sup>University of Colorado Anschutz Medical Campus, Aurora, CO

**Disclosures:** Jake Tinsley (N), Dana Carpenter (N), Jason Stoneback (Revivo International, back2mobility, AQ Solutions, Validus Cellular, Smith & Nephew, NuVasive Specialized Orthopedics), Brecca Gaffney (N).

**INTRODUCTION:** Bone-anchored limbs (BALs) are alternatives to traditional socket-based prostheses that anchor the prosthesis directly to the residual limb via a skeletally integrated implant [1]. BALs have demonstrated improvements in patient-reported outcomes [2] and improved biomechanical factors (such as step symmetry and joint motion) [3,4], but mechanical complications (i.e., implant loosening) can exist [5,6]. What patient parameters are most significant in causing these complications, which may be directly related to bone-implant interface stresses, is unknown. We recently developed a novel finite element analysis (FEA) methodology that integrates patient-specific biomechanical parameters but has currently only directly investigated estimated stresses and strains [7]. In this study, patient-specific parameters were related to dynamic stresses calculated in patients transfemoral (TF) BALs to investigate what factors most strongly correlate with residual limb stresses, to allow for better clinical judgment in patient selection and post-operative treatment for those with TF BALs.

**METHODS:** With Institutional Review Board approval, motion capture data were collected from ten individuals with TF BALs (age  $51.3 \pm 10.8$  yrs, BMI  $25.8 \pm 3.8$  kg/m<sup>2</sup>, time since amputation  $14.9 \pm 12.7$  yrs) during overground walking at self-selected speeds ( $0.98 \pm 0.15$  m/s) using 38 reflective markers and six force plates to record kinematics and ground reaction force. Computed tomography (CT) scans of the pre-operative residual limbs were collected and segmented to generate 3D geometries of the residual femur. Subject-specific musculoskeletal models were built using established methods [8] to analyze movement patterns, muscle forces, and joint loading. These data were combined in an FEA to estimate stresses at regions of interest (femoral head and neck, trochanteric and subtrochanteric, diaphysis, and implant) throughout loading phase of self-selected walking using a previously defined methodology [7]. Subject characteristics (age at implantation, height, mass, post-operative body mass index (BMI), time since amputation, self-selected walking speed (SSWS), BAL implant length, mean joint force and mean muscle force throughout stress analysis, and regional bone mineral density (BMD)) were correlated with the mean of patient maximum stress within each anatomical region of interest using Pearson's *r* correlation coefficient.

**RESULTS:** Individual associations with the highest positive correlations include average muscle force with diaphyseal stress ( $r = 0.80$ ), time since amputation and implant stress ( $r = 0.76$ ), and time since amputation and femoral neck stress ( $r = 0.73$ ). Individual associations with the highest negative correlation include post-operative mass and trochanteric stress ( $r = -0.79$ ), post-operative BMI and subtrochanteric stress ( $r = -0.72$ ), and post-operative mass and subtrochanteric stress ( $r = -0.71$ ).

**DISCUSSION:** In this subject-specific analysis, we identified that time since amputation, self-selected walking speed, and body mass were strongly correlated with residual limb stresses during walking in transfemoral BAL users. Notably, a longer interval post-amputation was associated with higher stresses at the implant interface and femoral neck; this suggests that a longer time since original amputation may significantly alter the loading pattern on the residual limb. Similarly, faster walking speeds and increased muscle forces amplify diaphyseal stresses, highlighting the mechanical trade-off between mobility and skeletal loading. In contrast, greater overall mass and BMI were linked to reduced localized stresses, possibly owing to altered gait mechanics and structural adaptations of the residual limb (such as increased cortical thickness) that distribute mechanical loads more evenly. These findings suggest that patient history and functional parameters may influence bone-implant loading in ways that could affect bone remodeling, and thus ultimately the risk of loosening and mechanical complications; alternatively, demographic factors such as age or implant length appear to be less influential.

**SIGNIFICANCE/CLINICAL RELEVANCE:** By integrating dynamic FEA with individual patient parameters, this work suggests residual limb stresses are most influenced by time since amputation, walking speed, and BMI in individuals with BALs. Clinicians can leverage these insights to refine candidate selection, and to customize post-operative protocols. Ultimately, incorporating these weightings into pre-surgical planning could reduce the risk of mechanical complications, improve long-term implant stability, and enhance functional outcomes for individuals choosing BALs.

**REFERENCES:** [1] Thesleff et al. *ABME*. 2018 [2] Leijendekkers et al. *Disabil. Rehabil.* 2017 [3] Gaffney et al. *Clin. Orthop. Relat. Res.* 2025 [4] Ravari et al. *Prosthet. Orthot. Int.* 2024 [5] Lee et al. *Med. Eng. Phys.* 2008 [6] Leijendekkers et al 2008 [7] Tinsley J et al. *SSRN*. 2024. [8] Vandenberg N et al. *J. Biomech.* 2023.

**ACKNOWLEDGEMENTS:** This study was supported by the University of Colorado Bone-Anchored Limb Research Group and National Institute of Health (R03HD111012 and UL1TR002535).

