Compliant Joint Reconstruction

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INTRODUCTION: Natural human movement relies on healthy joints. When joints are damaged due to pathology or injury, mobility can become severely limited and painful. Although advancements in orthopaedic surgery have provided options for replacing or reconstructing most joints, conventional implants do not last forever. Primary joint-reconstruction efforts typically focus on resurfacing the damaged joint with synthetic materials; as a result, the most common non-infectious causes of revision include i) aseptic loosening via wear-induced osteolysis and ii) instability [1]. Current implant designs address these failure modes separately by i) selecting materials to reduce particulate wear and ii) over-constraining implants to prevent dislocation. Over-constraint causes high loads at both the bearing surface, increasing friction and expediting the wear process, and at the bone-implant interface, which can accelerate loosening. We propose a revolutionary new type of joint-reconstruction implant centered around compliant mechanisms, which are nuanced "springs" that guide motion via flexing and bending rather than rubbing, rolling, or sliding (Fig. 1a) [2]. These mechanisms are inherently stable and frictionless, thus addressing both the particulate wear and instability of conventional arthroplasty, without over-constraining the joint. Herein, we present a feasibility analysis of one such compliant mechanism, namely the cross-axis flexural pivot (x-pivot), to reconstruct the ankle, knee, and elbow joints. Our analysis is focused on the ability of this mechanism to provide sufficient flexion/extension and support internal joint reaction loads for 100 years at each joint.

METHODS: We selected the x-pivot for its ability to provide a large range of motion about a single rotational degree of freedom (DoF), while withstanding high axial loads orthogonal to the axis of rotation. We designed the implant bodies that connect the x-pivot to the surrounding bone such that the flexures were oriented in their strongest possible configuration for supporting joint-compressive loads (Fig. 1a) and parameterized the resulting geometry according to key features (blade thickness, length, width, etc.). Using this parameterized model, we generated >85,000 finite element analysis (FEA) simulations of stress within the isolated flexures under various loads (Fig. 1b) (Abaqus, Dassault Systems, 2019). These results were used to train a neural network (NN) that predicts simulated stress as a function of load and mechanism geometry. We then used the NN to predict flexure stress in a sweep across all mechanism geometries that fit within each joint-specific anatomical envelope, under corresponding joint-relevant loading conditions. Applied loads were based on biomechanical modeling studies [3,4], and direct measurements from instrumented implants, if available [5]. Peak-stress predictions were converted to implant lifetime using the material properties of Titanium 6Al-4V (Ti64) and the anticipated cycle-counts for each prescribed load profile (walking, stairs, lifting objects, etc.) [6]. For example, 100 years of 2,500 daily cycles of walking loads corresponds to a peak-stress objective of 484 MPa. Feasible geometries for the ankle, knee, and elbow were chosen from the NN results, and physical Ti64 shim models were validated through acute testing on a robotic testbench. Validation procedures included characterization of mechanism stiffness and assessment of low-cycle performance under target loading conditions.

RESULTS: Predictions from our NN were used to create feasibility landscapes that illustrate the ranges of geometric parameter values from which a mechanism can be generated to last a given lifetime within the body. Figure 2 shows the ankle load profile and a corresponding feasibility landscape highlighting the 100-year lifetime contour. Similar evaluations were conducted for the knee and elbow. Ti64 shims were manufactured via wire electrical discharge machining based on geometries selected from each joint's feasibility landscape. Our chosen ankle mechanism is 55 mm wide and comprised of flexures set at a 60° angle with respect to each other. Each blade is 50 mm long, with a thickness spanning 0.5 mm at the blade center and 1.5 mm at the blade ends. The ankle-specific shims were assembled in an x-pivot configuration, and loads were applied via a 6-DoF serial robotic manipulator (KUKA). This mechanism supported a 36° range of motion (14° dorsiflexion + 22° plantar flexion), including the minimum expected compressive load of 420 N at full plantar flexion. Stiffness was characterized by hanging weights from one end of the mechanism and measuring the angular deformation (Fig. 3). The ankle x-pivot produced a stiffness of ~0.07 Nm/deg (~4 Nm/rad). Analogous validation routines will be presented for the knee and elbow mechanisms.

DISCUSSION: We present an innovative implant architecture for reconstructing human joints comprised of frictionless and inherently stable compliant mechanisms. Preliminary data from FEA and benchtop testing suggest that the x-pivot mechanism, in particular, is capable of supporting the dominant loads and rotational displacements associated with flexion/extension during walking and other activities of daily living. Future work will involve additional acute benchtop testing, including the application of significantly higher compressive loads across each joint-specific range of motion. Torque-angle curves will be recorded across each prescribed trajectory to ensure all deformation is purely elastic. Further, we will perform high-cycle fatigue testing to better assess mechanism lifetime and evaluate stability during out-of-plane loads. This fundamental reimagining of orthopaedic joint reconstruction has the potential to alleviate pain and restore joint function for a lifetime.

SIGNIFICANCE/CLINICAL RELEVANCE: The past couple decades have seen a plateau in the longevity of implants for joint replacement/reconstruction. The objective of the proposed research is to advance a revolutionary new type of implant that directly addresses the driving factors of revision present in conventional implants and provides permanent solutions to joint pathology.

REFERENCES: 1. Sadoghi et al. (2013); 2. Howell (2001); 3. Stauffer et al. (1977); 4. Kincaid et al. (2013); 5. Bergmann et al. (2014); 6. Janecek et al. (2015)
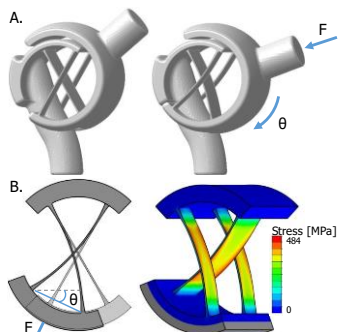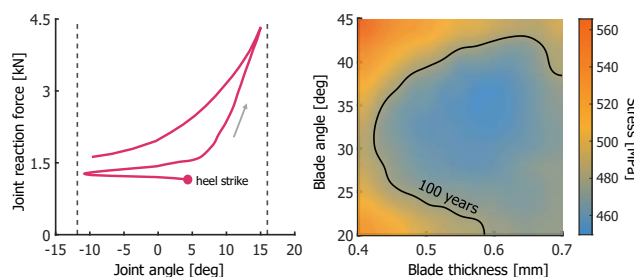
Fig. 1: Compliant mechanism modeling.

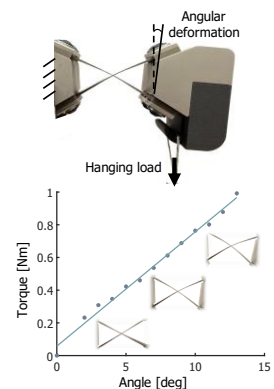Fig. 2: Ankle joint loading conditions and two-parameter feasibility landscape.

Fig. 3: Benchtop stiffness results.