INTRODUCTION: The proximal humerus is one of the most common sites for osseous sarcoma and osteosarcoma. Current reconstruction approaches after tumor resection include a cemented allograft-prosthesis composite, osteoarticular allograft, and modular tumor prosthesis. Although endoprostheses have been reported to have relatively lower complication rates, reconstruction of the humerus after tumor resection continues to be a challenge because of several common complications such as proximal migration, subluxation, nonunion and aseptic loosening of the stem. Obtaining proper off-the-shelf components for pediatric patients is especially challenging because most standard components are sized and shaped for the more common adult cases. Additive manufacturing (AM), commonly referred to as 3D printing, has the ability to produce complex and property tailored geometries, which can be used to make patient-specific implants that could reduce postoperative complications. While currently reported efforts have focused on AM patient-specific implants for maxillofacial, hip and knee joint replacements, and dental surgeries, there have been no reported study on AM reconstruction of proximal humerus tumors after resection. The aim of this study is to develop a systematic procedure for the design-analysis-AM of patient-specific prosthesis for the proximal humerus after tumor resection.

METHODS: IRB-approved magnetic resonance imaging (MRI) data of a 9-year old patient diagnosed with proximal humerus osteosarcoma was obtained (Fig. 1A). DICOM data was used for image segmentation and anatomy reconstruction in Avizo (Fig. 1B). The 3D reconstructed anatomy of the patient was imported into Geomagic Design X (3D Systems) to develop parametric design on a polygonal surface model of the bone. Measured anatomical dimensions from the MRI images and the 3D reconstructed anatomy were used to design a patient-specific prosthesis. During the design process flow, special attention was given to the bone-implant interface in order to facilitate for bone ingrowth. ElementPro (nTopology) was employed to create porous structures with cube vertex centroid topology of unit cell dimensions - 7mm and 3 mm and varying strut thickness of 0.8-2 mm - at the surgical neck and distal-cortical contact of the prosthesis, respectively (Fig. 1C). Prior to AM fabrication, static finite element analysis (FEA) was conducted (Abaqus/cae 2017, Dassault Systems) to evaluate the mechanical strength of the patient-specific prosthesis under postoperative physiological loading available in the OrthoLoad database† (Fig. 1D). The patient-specific prosthesis was fabricated using biocompatible Ti-6Al-4V virgin powder in an electron beam melting (EBM) machine at a layer thickness of 90 µm (Fig. 1E-F). Surface morphology of the 3D printed prosthesis was characterized using Axio imager M2m (Zeiss) (Fig. 1G).

RESULTS: A patient-specific prosthesis was designed based on patient’s 3D reconstructed anatomy, avoiding residual limb length discrepancies and angular deformities, and potentially improving fixation with distal bone. Based on the covering sphere algorithm, porosity of 76.8% and 69.8% was achieved at the surgical neck and distal-cortical contact of the prosthesis, respectively. In addition, the designed porous structure increased the effective surface area by 65.4% along with weight reduction of 9.1%. Prior to fabrication, maximum von misses stresses experienced by the prosthesis (about 500 MPa) was compared with yield strength of Ti-6Al-4V (1100 MPa). Surface roughness of Rₐ=144 µm and Rₐ=29 µm was achieved with the EBM technique (Fig. 1G) which is within the range of recommended surface morphology for osseointegration*. 

DISCUSSION: This study shows the potential of AM to personalize prostheses for osteosarcoma patients according to the patient’s anatomy, bone quality and soft tissue. In addition to our design collaboration between engineers and a senior musculoskeletal oncologist, quantitative analysis was limited to static numerical modeling to evaluate the mechanical behavior of the design. Cyclic loading (fatigue) FEA and standard biomechanical testing using synthetic bones will be conducted.

SIGNIFICANCE/CLINICAL RELEVANCE: This study provides a systematic process flow for the design and AM fabrication procedure for the reconstruction of the proximal humerus following tumor resection. This approach of applying AM for patient-specific prostheses may eliminate residual deformities and improve implant fixation, especially in uniquely challenging cases such as pediatric bone tumor resection.


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Fig. 1: (A) Patient’s DICOM data before tumor resection, (B) Anatomy reconstruction, (C) Designed prosthesis, (D) FEA, (E) Principle of EBM, (F) 3D printed prosthesis, and (G) Surface roughness assessment