INTRODUCTION: Measuring the healing status of a bone fracture is important to determine optimal clinical care. However, currently, there are no objective techniques in the clinic to define the healing status. In response, there have been efforts in recent years in the development of new objective tools to quantify structural bone healing: virtual biomechanical testing and in vivo implantable sensors. Implantable devices can continuously measure the healing status of fracture fixation constructs in situ, while subject-specific virtual biomechanical tests can noninvasively determine callus structural integrity at single time points. Despite their potential to objectify healing assessment, neither method is integrated into clinical practice with further evidence of their benefits required. This study aimed to correlate continuous data from an implantable sensor assessing healing status through implant load monitoring with computer tomography (CT) based longitudinal finite element (FE) simulations in a large animal model.

METHODS: This study utilized the data from a previous preclinical study of an ovine tibial osteotomy model with gap sizes ranging from 0.6 to 30 mm². The osteotomies were fixed with a plate (titanium or stainless steel) and were equipped with a strain sensor (AO Fracture Monitor). Sensor signal was collected over several months, and CT scans were acquired at four-week time points. The animal experiments were approved by the local responsible ethics committee. Specimen-specific FE models at each CT time point were constructed from the CT scans (Figure 1). Bone and fracture callus were modeled with element specific material properties to capture the heterogeneity of the tissue density seen in the CT scans, while the plate, screws, and sensor were imported as computer aided design (CAD) parts. CT image segmentation was performed in Amira 3D (v2021.2, Thermo Fischer Scientific), hardware assembly was performed in Solidworks (v.2022, Dassault Systems), and meshing for use in FE analysis was performed in Simpleware (v.2017, Synopsys). Finally, FE models were imported into Abaqus (v2021, Dassault Systems) and virtual mechanical tests were performed. For each scan, two FE analyses were performed (Figure 1). First, a virtual torsional rigidity (VTR) test of the bone was performed where the distal end was fixed, and the proximal end was rotated 1 degree, measuring the healing status of just the bone and fracture callus. Second, a model of the bone-implant construct with the sensor was chosen to represent the real-world situation as closely as possible. In this model, the distal end was fixed with a pin support and a 500 N axial load was applied to the proximal end. The strain value was calculated at the same location as the strain sensor in the implanted AO Fracture Monitor and a relative implant load (RIL) was calculated as the max value of the sensor data. The longitudinal simulation results were compared to the sensor data at corresponding time points. A cohort-specific empirical healing rule was employed consisting of (1) a change of < 5% of the max value in the signal from the previous month that was (2) sustained for 6 weeks with (3) a drop below 21% of the max value.

RESULTS SECTION: Data from eight sheep were used in this study. Linear regression analysis was performed to relate the RIL of the in vivo data extracted at the dates of CT scan acquisition and the two FE simulation outcomes (VTR and RIL). Strong correlations of $R^2 = 0.7$ and $R^2 = 0.8$ were found in the torsion model and the virtual sensor construct models respectively. The healing outcomes between the sensor and the two FE models closely agreed for all eight animals, with six animal healing in the observed time and two having delayed- or non-unions (Figure 2).

DISCUSSION: Virtual biomechanical testing and in vivo sensors are promising technologies to address the lack of objective healing assessment. In this study, subject-specific FE models were compared for the first time to continuously acquired in vivo data in eight sheep models, and the results demonstrated that both FE simulations strongly correlated to the in vivo sensor data for the assessment of fracture healing. However, the complexity of the FE model does not seem important for the assessment of healing as both FE models correctly identified the delayed and non-healing cases based on the healing completion criteria. In this prediction, VTR directly assesses the stability of the callus, while the virtual sensor model which assesses the stability of the entire bone-implant construct. The study is not without limitations. First, CT-based FEA is its snapshot nature with data only available where a CT scan was taken, and second, boundary conditions in the virtual tests were idealized to a generalized and not specimen-specific loading. Nevertheless, the results demonstrated the ability of longitudinal virtual testing to quantitatively define callus structural integrity and to replicate the healing prediction of continuous in vivo data across different ovine tibia osteotomy models based on criteria specific to this cohort. This study demonstrates consistency between these two emerging technologies, virtual testing techniques and in vivo sensors, as promising methods in objectifying the assessment of healing and allow for better diagnosis and early reaction to complications.

SIGNIFICANCE/CLINICAL RELEVANCE: Currently there are no clinically available objective measures for bone healing status after a fracture. The methodology present in this study is an objective technique that is readily translatable to the clinic with promising results in both the virtual tests and the implantable sensor technologies.


Figure 1: 3D rendering of a) torsion model and b) bone-hardware construct.

Figure 2: In vivo sensor relative implant load (RIL; gold), corresponding interpolated VTR (red) and virtual sensor RIL (blue) for four exemplary animals. Healing indicated by a * for animals #1 and #6 but was not detected for #7 and #8.