Implantable Sensors Detect Bone Healing in Sheep Mid-Diaphyseal Femoral Fractures

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INTRODUCTION: Implantable wireless sensors have revolutionized our understanding and management of diseases through continuous, precise, and personalized recordings of physiological signals[1]. In musculoskeletal research, and particularly in bone, implantable sensors have the potential for capturing the complex mechanical and biological changes involved in bone remodeling and healing. We recently reported the development of a wireless, battery-free, multimodal platform that attaches directly to bone tissue, known as osseosurface electronics (OE)[2,3]. OE devices consist of a thin flexible substrate capable of housing various sensing modalities (mechanical strain, temperature) and transmitting data wirelessly. In this study, we explore the use of OE devices for monitoring mid-diaphyseal femoral fractures in sheep. We hypothesize that OE devices can effectively monitor changes in bone mechanical strain properties during both union and non-union fracture healing processes.

METHODS: All animal experiments were conducted under an approved IACUC protocol. Six adult wethers weighing between 49 and 81 Kg were anesthetized using ketamine and isoflurane. An 8 cm incision was made along the lateral thigh of the left hind limb and the interval between the quadriceps and hamstrings was developed to expose the femur. An osteotomy was created using a custom cutting guide and stabilized with a custom 8 mm-diameter intramedullary nail with proximal and distal interlocking screws. Two OE devices were secured proximal and distal to the fracture site using 2-0 Vicryl sutures with the sensing element oriented along the long axis of the bone (Fig 1A). The incision was closed in a layered fashion. Radiographic images were acquired weekly and evaluated by a licensed orthopedic surgeon. Data collection began approximately 3 weeks post-implantation to allow for weight-bearing during walking. Animals were walked for 2 minutes on a commercial treadmill at 2.6 km/hr with a camera placed sagittally to capture the movement of all four limbs. Data was acquired wirelessly through a coiled antenna placed superficially over the limb during walking. Strain data was time-synchronized to the video and analyzed by observing changes in strain magnitude during the loading and unloading phases of the gait cycle (Fig 1B). Sheep were euthanized and femora were explanted, µCT imaged, and mechanically tested to validate the healing state.

RESULTS: Radiographic images (Fig 1C Left) taken during the fracture healing recovery, show a clear difference in fracture healing between union and non-union outcomes in both callus size and fracture line presence. Weekly strain data collection demonstrated a progressive decrease in strain magnitude from the beginning of the walking regimen to around weeks 4-5 in both the union and non-union sheep (Fig 1C Right). After the lowest point of strain, the union sheep exhibited a progressive increase in strain for 4 weeks plateauing by week 10. This increase in strain correlates with the presence of bridging bony callus in the radiographic images, indicating the changing mechanical environment between the healing bone and fixation implant during bridging.

DISCUSSION: To the best of our knowledge, we are the first to demonstrate changes in bone strain characteristics in a sheep mid-diaphyseal femoral defect using implantable sensors. OE devices captured distinct changes in bone strain in union and non-union healing outcomes, highlighting the continuous change in bone mechanical properties during fracture recovery. Although this study served as a proof-of-concept for the use of OE devices in musculoskeletal research, one of its limitations was the use of an all-male sheep cohort. This limitation is due to the sourcing facility only having male sheep. Future studies will be focused on investigating differences in strain profiles during fracture recovery in various age- and sex-related cohorts.

SIGNIFICANCE/CLINICAL RELEVANCE: Fracture non-unions are major clinical problem resulting in prolonged hospital stays and increased healthcare costs. While current standards rely on radiographs, which fail to capture the dynamic process of bone healing, wireless implantable sensors overcome this limitation by providing continuous, quantitative strain data that can differentiate union from non-union outcomes in real time.

REFERENCES: [1] Yogev+ 2023 APL Bioeng, [2] Cai+ 2021 Nat Commun, [3] Kasper+ 2025 Sci Adv
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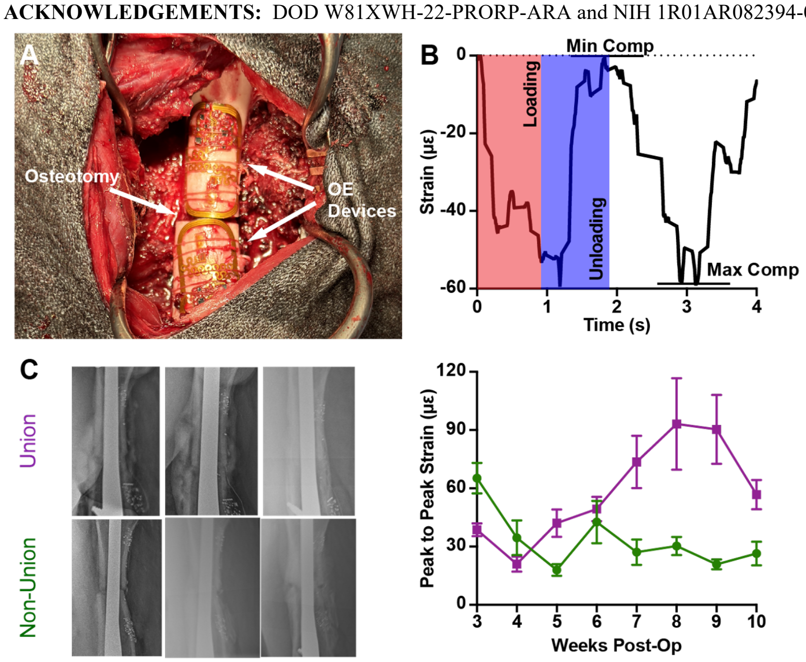

Figure 1. Monitoring of biomechanical strain in mid-diaphyseal femoral fractures using osseosurface electronics (OE). (A) A mid-diaphyseal femoral defect is created and stabilized with an intramedullary nai, while two OE devices are positioned proximally and distally to the fracture site. (B) The gait strain data of sheep during treadmill walking is shown, with red area indicating the loading phase and blue the unloading phase of the gait cycle. Peak-to-Peak Strain is calculated by the difference in magnitude between the maximum and minimum compression points in one step cycle. (C) Representative anteroposterior-view radiographs illustrate femoral fracture recovery in sheep with cases of union (Purple) and non-union (Green). The graph represents weekly strain data from union and non-union animals over 3-10 weeks post-operation.