Preclinical validation of mechanoregulatory fracture healing simulations

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Introduction

Fracture management remains a significant clinical challenge, with non-unions accounting for approximately 5% of all bone fractures. Surgeons must select the most effective treatment strategy to optimize the healing outcome. Fracture healing simulations have the potential to predict the time course of healing, aiding in selecting treatment strategies by enabling timely diagnosis of potential complications and non-union risk assessment. This study aimed to validate a pre-existing mechano-regulatory fracture healing simulation algorithm [1] against data from a preclinical sheep study with an implanted sensor, including union, delayed- and non-union cases, for the first time. It was hypothesized that specimen-specific differences could be replicated in the predicted time course of healing.

Materials and Methods

Subject-specific finite element (FE) models of bone-implant constructs were developed for eight animals from CT-scans for use with the iterative healing simulation algorithm. A pre-established fuzzy logic engine calculated tissue differentiation changes based on local strains predicted from axial loading and updated the material properties of the FE models accordingly for 112 days of healing (Figure 1). After each iteration step, virtual torsional rigidity (VTR) was calculated to assess the structural healing progression status and calculate specimen-specific healing curves. For quantitative validation, the simulation results (prognostic VTR and *in silico* plate strain) were compared to their respective validation parameter (CT-based diagnostic VTR [2] and sensor data based *in vivo* relative implant load (RIL)). For qualitative validation, predicted callus tissue differentiation was compared to *in vivo* X-ray images.

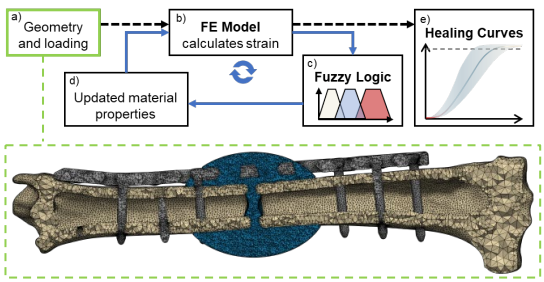

Fig. 1 Diagram of the mechanoregulatory healing simulation process applied on specimen-specific FE models, including an anteroposterior cut view of the bone-implant construct and the spheroid healing region.

Results

The simulations successfully predicted spatial and temporal tissue differentiation (Figure 2b). Significant differences between the predicted healing curves were identified and allowed for detecting trends towards the healing outcome and differentiating between union and delayed-/non-union cases.
However, the predicted healing time courses were accelerated compared to the *in vivo* data (Figure 2a).

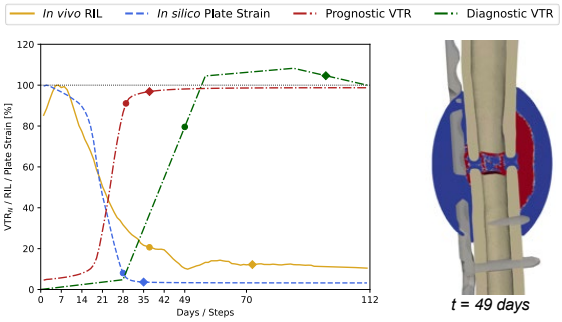

Fig. 2 (a) Simulated healing curves and corresponding in vivo and diagnostic VTR data for one exemplary specimen. (b) Predicted callus formation after 49 days.

Discussion

This is the first study validating specimen specific healing models against preclinical data with continuous sensor monitoring. Overall, the outcomes demonstrated successful application of the healing simulation algorithm but only partial validation of the simulation results. The findings were in alignment with relevant literature but highlighted the limitations of predicting subject-specific healing time courses with the existing algorithm, especially for non-unions cases. Despite this, the potential of the simulation to predict healing trends was demonstrated. Further adaptations and improvements are necessary before this tool can be implemented into clinical settings.

References

[1] Schwarzenberg et al., J Biomech, 2021. 118: p. 110300.
[2] Hetreau et al., J Orthop Res, epub, 2024.

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