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Biomechanics of fracture healing: how best to optimize your construct in the OR

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Abstract Orthopaedic surgeons routinely assess the biomechanical environment of a fracture to create a fixation construct that provides the appropriate amount of stability in efforts to optimize fracture healing. Emerging concepts and technologies including reverse dynamization, "smart plates" that measure construct strain, and FractSim software that models fracture strain represent recent developments in optimizing construct biomechanics to accelerate bone healing and minimize construct failure.

Keywords: biomechanical, fracture union, reverse dynamization, model, strain, smart plate

1. Introduction

Orthopaedic surgeons are constantly faced with many implant choices and implant configuration options when building a construct for fracture fixation. Multiple considerations must be made to assemble the optimal construct for successful bone healing, which relies on achieving ideal balance between various mechanical and biological factors.[1] For example, key mechanical considerations include the fracture geometry, bone quality, plate length/material, number/distribution of screws, and use of unicortical/bicortical screws. If any of these components are not appropriately considered or selected, it could result in a construct failure, such as screw pullout or breakage, plate breakage, and deformity, resulting in nonunion or malunion. Among the biological considerations are soft tissue integrity, vascularity, and the patient's physiology. Finally, there are considerations that are effectively both mechanical and biological including loading conditions (axial, shear, torsion/rotation) and the magnitude of interfragmentary strain (IFS). For instance, a rigid construct produces low strains and results in primary bone healing. Alternatively, a flexible construct creates higher strains, initially forming cartilaginous callus or secondary bone healing. However, if the loading conditions or the magnitude of strain are too high (>15%) or too low (0%), the healing response might fail, resulting in either hypertrophic or atrophic nonunion.[2]

While absolute stability/rigid fixation was initially thought to be the proper method for fracture fixation, Stefan Perren developed strain theory, demonstrating the link between the amount of relative motion and callus formation.[3,4] Ilizarov's alternative principles of tension stress/distraction of bone contradicted the OTA/AO principles of compression plating, revealing that relative motion can also achieve successful bone healing.[5] Decades later, Goodship and Kenwright[6] advocated for the importance of limited axial micromotion or relative stability and reported the detrimental effects of shear and torsion/rotation. In later work Gautier and Sommers[7] and Michael Bottlang[8,9] confirmed the many benefits of relative stability. Nevertheless, the ideal requirements for optimal bone healing remain unknown, partly related to the shortcomings of these landmark contributions. For example, absolute stability may only best in a subset of low-energy fractures, while the values of optimal strain within the fracture site are arbitrary, and at this point, it cannot be determined in practice. The study was deemed exempt from Institutional Review Board and Animal Use Committee Review.

2. Reverse Dynamization

Dynamization, a controlled motion strategy where fixation stability is initially rigid and then converted to a more flexible construct, is an alternative, emerging concept for achieving bone healing.[10] This process is thought to optimize healing by accelerating bone remodeling. However, conventional dynamization remains controversial and has not greatly influenced or improved clinical practice.[10]

For dynamization, questions exist regarding when to dynamize, how much motion to allow, and for how long are still unclear. However, numerous studies have demonstrated that construct stiffness should be neither too rigid nor too flexible. Furthermore, it has been shown that axial micromotion stimulates callus formation and more rigid fixation promotes remodeling. Importantly, the biological characteristics of the forming tissue changes over the course of bone healing, which requires specific mechanical considerations to optimize the healing response.

Accordingly, the concept of reverse dynamization (RD) has been introduced as a more effective method to optimize bone

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healing.[1,2] It involves early flexible fixation, allowing continuous micromotion and encouraging callus formation. Once substantial callus has formed, stabilization is converted to rigid fixation under which the soft callus is quickly converted to hard callus, leading to more rapid union. Several animal models[11–14] and limited clinical studies[15,16] have repeatedly confirmed superior bone healing using the RD regimen compared with any other method. Claes et al[17] demonstrated that dynamizing a fracture during the early phase of healing resulted in nonunions, where continuous micromotion in the early healing period prevented maturation of sprouting vessels and led to incomplete callus remodeling.[14,18] When dynamization or reverse dynamization was applied during later stages of bone healing, there was no difference in the healing outcomes because at this point, most mechanical loads are transferred through the callus itself, while the construct/fixator stiffness contributes very minimally to the overall stability.[19,20]

Current evidence indicates that bone healing/remodeling can be accelerated by optimizing the biological response through mechanical cues dictated by the construct characteristics.[1,2,11–14] Furthermore, controlling the timing and spatial relationship of the introduction of these mechanical cues ultimately determines the type and the amount of tissue formed. Biologically, successful bone healing always begins with hematoma formation/inflammation followed by the soft callus phase and culminates with the remodeling phase, which can take years to complete. The goal of RD is not to change or eliminate any of these phases but to simply shorten the soft callus phase to enhance healing and initiate a rapid transition to remodeling (Fig. 1). The RD regimen optimizes this process and provides a modern strategy to accelerate bone healing and tips the balance in favor of more rapid and reliable bone union, thereby likely minimizing the incidence of nonunion. Further innovation in surgical techniques and implant design, as well as determining the ideal magnitude of the IFS, will be required to definitively optimize bone healing. Until then, magnetic/motorized nails[15] or external fixators[16] will continue to be used to actively manipulate the mechanical environment surrounding the fracture, facilitating modification of the construct stiffness without requiring a secondary invasive procedure.

3. "Smart" Fracture Plate Add-On to Assess Callus Stiffness

Currently, the diagnosis of fracture healing and nonunion after plate osteosynthesis is based on clinical examination and radiographic assessment, both of which are subjective. Conversely, fracture callus stiffness may be an objective indicator of fracture healing. Initially, after osteosynthesis, loads applied to the bone are primarily transmitted through the plate. However, as callus stiffness increases, the callus bears load proportional to its stiffness. As force transmitted through the bone increases, forces through the plate decrease. Thus, measuring the forces transmitted through the plate during fracture healing can provide an objective indicator of healing progression. However, there are currently no techniques for measuring/assessing these objective data. A novel add-on accessory was recently developed which converts a standard fracture plate into a "smart" plate by facilitating the measurement of forces transmitted through the plate. The purpose is to use the "smart" fracture plate add-on to distinguish between phases of fracture healing in an in vitro biomechanical model during progression of simulated callus formation.

To confirm the concept of the "smart" plate, a 5-mm osteotomy was created in 3 biomechanical composite femurs (Sawbones; Vashon Island, WA) to simulate an OTA/AO 33A-3 fracture. The simulated fracture was stabilized with a titanium anatomic distal femoral locking plate (Stryker; Mahwah, NJ). A wireless force sensor and small add-on accessory were placed on the outside of the plate and secured to the plate–femur construct using bone screws (Fig. 2). The accessory converts the slight bending of the plate under axial load into a transverse force, which is measurable by the sensor. Specimens were then placed in a mechanical testing machine (MTS Systems; Cary, NC) oriented with a 6-degree valgus anatomic axis and loaded up to 700 N to simulate single leg stance. Specimens were loaded first with the osteotomy defect empty (acute healing) and then sequentially filled with silicone (to simulate early callus) and then polymethyl methacrylate (to simulate hard callus). Data were analyzed to determine correlations between applied axial load, transverse forces measured in the plate, and the degree of simulated healing.

Under axial load, the plate bends slightly and the add-on accessory acted as a mechanical amplifier to convert the bending

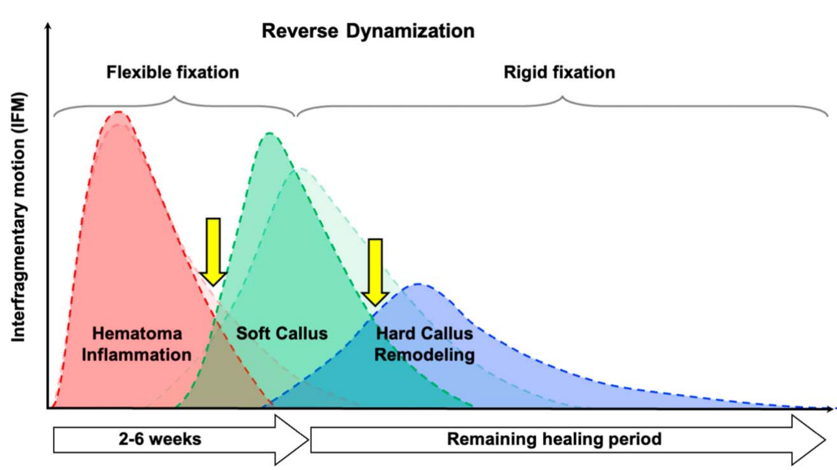

Figure 1. A schematic representation of the reverse dynamization regimen, including the typical timeline for the relevant phases of fracture healing hematoma/inflammation, soft callus, and hard callus/remodeling. An initial period of flexible fixation for the first 2–6 weeks promotes maximal soft callus formation. Subsequent conversion to rigid fixation accelerates more rapid progression toward hard callus/remodeling and complete union.

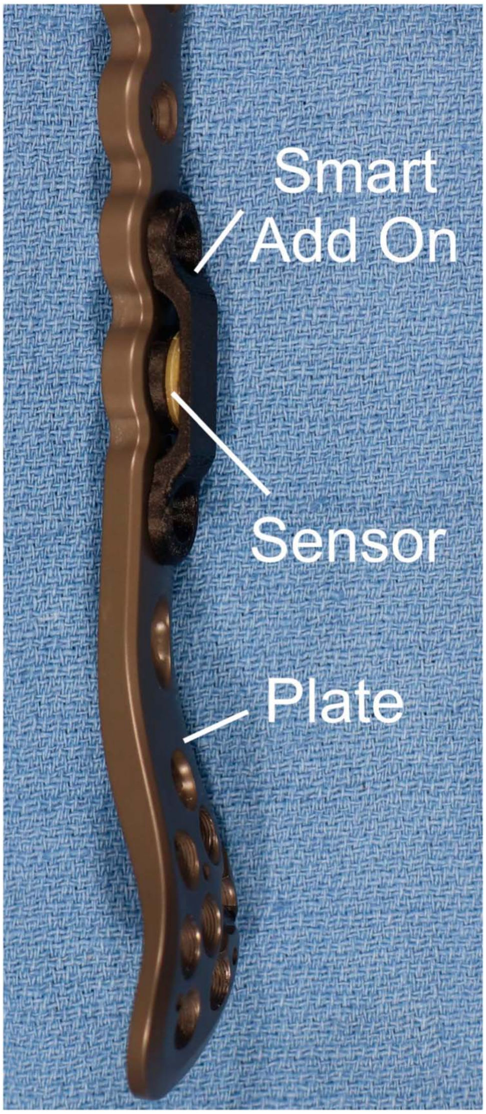

Figure 2. “Smart” plate with sensor and add-on plate attachment.

into a transverse load applied to the sensor. A strong correlation was observed between applied axial load and transverse force measured through the plate ($R^2 > 0.96$). Data demonstrate statistically significant differences ($P < 0.05$) between each phase of healing with as little as 150 N of axial load applied to the femur. The differences became more prominent as applied load increased. The forces measured through the plate were significantly reduced as callus stiffness increased from acute (100%), to early callus (66.4%), and to hard callus (29.5%).

Forces measured through the “smart” fracture plate using the novel add-on accessory correlated with simulated fracture callus stiffness with no modifications required to the plate itself. The system was sufficiently sensitive to distinguish stages of healing with as little as 150 N of applied axial load—analogous to partial weight-bearing. The implementation of the novel wireless sensors and add-on accessory demonstrates early efficacy for objective assessment of fracture healing. These objective data may enable early diagnosis of nonunion and enhance outcomes for patients. Ultimately, the “smart” plate may be used to quantify fracture healing. Future work is necessary to evaluate the efficacy of this technology in vivo.

4. FractSim Software for Visualization of 3D Fracture Fixation Biomechanics: Effects of Fracture Healing

Biomechanics has fundamental importance in fracture surgery. Implants can mechanically fail due to plastic deformation or fatigue, especially in cases of nonunion. Implant failure can occur anywhere but is more likely to occur in devices that bear large loads. For example, a recent study by Reeb et al highlighted the importance of biomechanical considerations in distal femur fractures.[21] Strain conditions at the fracture site also influence callus tissue type and bone healing quality.[22] It is difficult to estimate localized strain magnitudes, and therefore, fracture fixation biomechanics can be both complex and counterintuitive.

Computational simulations offer an attractive framework to improve our understanding of relationships between implants, mechanical loads, and fracture healing. In orthopaedics, most simulation-based education is focused on simulation of the surgical procedure itself.[23] Conversely, there is a lack of visualization of how construct decisions affect postoperative biomechanical stability. The FractSim software helps to address that gap by combining finite element computer simulation[24] with a user-friendly, interactive interface. In a previous study, we demonstrated improvements in biomechanical knowledge after a session with FractSim.[25] The aim of this study was to add visualization of the effects of fracture healing to FractSim (Fig. 3).

This study focused on simplified bridge plating, modeled with a large fracture gap to facilitate visualization. For visualization of the callus, the results from a large sheep study[26] were adapted to provide realistic geometries and to approximate increases in bone density over time. Models included a narrow large fragment stainless steel locking plate, a bone diameter similar to a 50th percentile male femur, a simple axial force of one bodyweight, and a linear increase in number of daily loading cycles. Relationships from the literature were adapted to simulate changes in fracture callus stiffness over time.[27] In the center of the plate, maximum stresses were used to compute fatigue damage and cycles to failure using Goodman equations and Miner’s rule formulas. Validity of the finite element models (without callus) was assessed using benchtop experiments with fourth generation Sawbones and 3D motion analysis. The results for interfragmentary displacement showed good agreement between the model and experiment for 3 different working lengths.

The FractSim software currently allows users to simulate 4 different healing capacities: normal healing, delayed healing, nonunion, and no healing. For normal healing, fracture stiffness is assumed to increase substantially after 4 weeks, whereas for delayed healing, the times are doubled. For nonunion, increases in callus stiffness halt at about 7 weeks. In addition, a variety of postoperative weight-bearing/loading plans are available, based on 10%, 50%, and 100% weight-bearing. The software allows the user to prescribe different weight-bearing levels at 3 different time points. Once the user selects healing capacity and loading plan, FractSim displays plots of maximum stress and cumulative implant damage over time. Once all inputs are defined, the software provides a 3D visualization of gradual changes in callus morphology, construct displacements, and stresses. The 3D view can be manipulated to make changes in zoom, rotation, and changes in transparencies.

A variety of educational concepts can be shown with this new fracture healing module in FractSim, including

- Large decreases in plate stresses due to small increases in callus stiffness during early stages of normal healing.

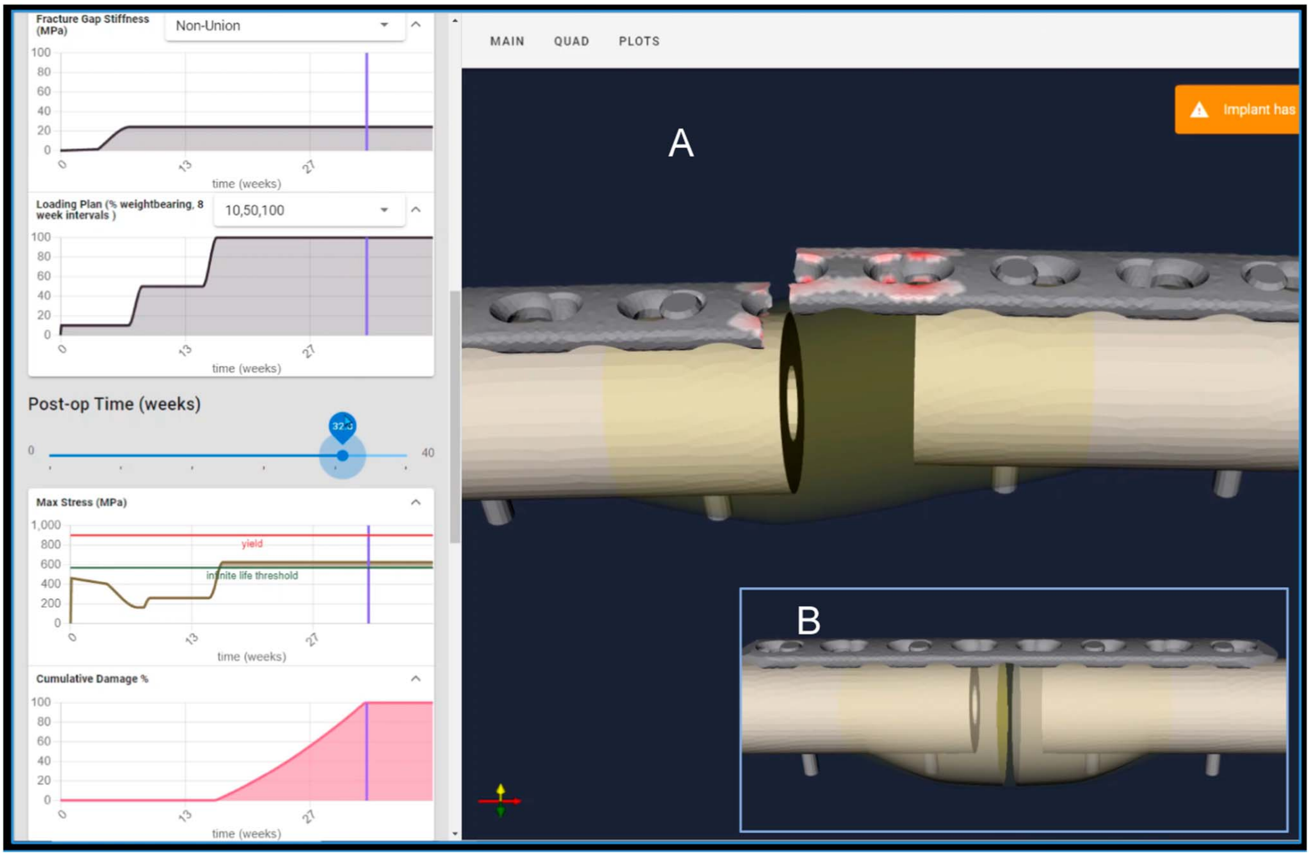

Figure 3. A, A snapshot from latest version of FractSim software, including effects of fracture healing. In the upper left, the surgeon has selected a nonunion, in which fracture gap stiffness (y-axis) stops increasing at 6 weeks (x-axis). Below that, the selected postoperative loading plan shows how load magnitude increases over time. In the middle left, the slider bar (and corresponding vertical purple lines) can be moved by the surgeon to advance through postoperative time and "immediately" visualize continuous gradual changes in fracture callus morphology and plate stresses. The bottom plots show maximum plate stress, infinite life and yield limits for comparison, and associated cumulative fatigue damage. At the instant shown above, the damage has accumulated to 100%, resulting in a sudden visible breakage in the plate. The surgeon can then make new selections to attempt to increase construct life for this hypothetical patient, by changing the fracture fixation construct, improving healing capacity (eg, through bone grafting), or modifying the loading plan. B, For comparison, a normal, nearly bridged callus with low plate stresses is shown in the inset.

- The importance of maintaining stress levels below the infinite life threshold.
- How cumulative damage builds over time if stresses are above this threshold (eg, in a nonunion scenario), potentially resulting in eventual fatigue failure.
- How risk of fatigue failure can be mitigated in nonunion or delayed union scenarios.
- Potential risks of yield or fatigue with early full weight-bearing, in this bridge plate fracture scenario.

FractSim provides a new way to visualize the interactions between bones and callus, implants, healing capacity, and postoperative loading important for construct life. Ongoing development activities include developing an autonomous, adaptive virtual coach that guides the learner through various educational modules.

5. Biomechanics of Fracture Healing: Where Might We Go From Here?

With so many biomechanical and technological advances, as it relates to fracture treatment healing, where we might we go from here? To answer this question, we should ask what the injured individuals want. They want to return to their previous function as soon as possible with a low economic burden. However, our current efforts, aimed at accelerating and improving biomechanical restoration, do not necessarily lead to commensurate functional restoration. Using the geriatric distal femur fracture as an example, the addition of a plate to an intramedullary nail or a distal femoral replacement allows for more weight-bearing immediately after surgery. Although these approaches seem clinically practical, they may not create biological or biomechanical milieus that lead to improved clinical results for a geriatric patient.

The next generation of fracture care using smart implants may provide feedback or mechanical adaptability that will allow surgeons to "fix smarter" while lowering surgical and implant footprints. However, there are still many questions that must be addressed going forward. For example, could analytics of mechanical and biologic variables at the time of injury and before fixation direct choices made regarding implant stiffness? To put it another way, could smarter preoperative planning eliminate the need for adaptable implants? Alternatively, could an implant adapt to (or prevent) a developing hypertrophic non-union by changing rigidity to allow for callus consolidation? It is likely that the solution will involve integrating these 2 concepts. In the future, information-based preoperative plans and smart implants could use patient-specific variables to plan and execute a feedback-based proactive biomechanical treatment plan by calculating and creating the optimal strain environments over the time course of healing.

As we consider these most challenging injuries in the realm of fracture repair, we must accept that we have not been successful at allowing motion and function under high loads. Weight-bearing and demanding functional activity after fracture repair has remained elusive. Expanding beyond internal fixation, we may want to reconsider our currently rudimentary passive bracing systems as means to actively restore bone health. One area of interest may include exoskeletons, which remain within the realm of science fiction in the clinical care of fractures at present.

Finally, in the context of considering such advanced adjuncts, we should not forget the importance and power of education. It is important to teach and emphasize proper soft tissue handling, appropriate reduction thresholds, and optimized application of rehabilitation principles. Improvements in these key areas of treatment decision making could partially obviate the need for technology and overcome our surgical and mechanical limitations. For those limitations that do remain, we should continue to explore new technologies and approaches, rather than limit our standards of care to paradigms that have served us well in the past.

6. Summary

Optimizing the biomechanical environment of the fixation construct remains a vital and challenging aspect of fracture fixation to guide appropriate bone healing. Several recent advances have been made to help surgeons create the appropriate strain conditions for primary or secondary bone healing. Reverse dynamization, “smart” plates, and FractSim are all developing technologies that may assist surgeons in the preoperative and postoperative setting to provide better patient care.

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