NORTHERN OHIO FOOT & ANKLE FOUNDATION

The Northern Ohio Foot and Ankle Journal *Official Publication of the NOFA Foundation*

The Evaluation of Bone Union

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The Northern Ohio Foot and Ankle Journal 1 (1): 1

The determination of bone union, whether it is following the reduction of a fracture or the fusion of a joint is a fundamental requirement within the orthopedic and podiatric field. Despite its necessity in dictating diagnosis and treatment plans, the process of determining fusion remain vague and devoid of a collective protocol. This review looks at the applications and limitations of current bone union determination techniques and their potential application within the foot and ankle.

Key words: Fracture Healing, Nonunion, Arthrodesis, Radiographic Union Scale, Fracture Stiffness

Accepted: February, 2015 **Published:** February, 2015

Non-union is commonly defined as a fracture or failed arthrodesis for more than 9 months that has not shown any radiographic signs of progressive healing for 3 consecutive months. It is a well-documented, serious complication of bone surgery with an annual incidence of 5-10% of all fractures in the United States. [1]. This excludes the non-union rates experienced within arthrodesis where for example non-union rates of ankle fusion range from 5-37% and 1st mpj non-unions occur at a recently reported rate of 5.4% [2,3]. Determining when a site is fused is an integral part of podiatric care; such confirmation dictates the weight-bearing protocol, possible hardware removal and the potential for future treatments. However despite the necessity to differentiate union from non-union, there remains a lack of unified agreement for the accepted definition and we are therefore obligated to question how any rate of union and non-union is derived. Ultimately this apparent deficiency of standardization impedes the decision making abilities of the physician, directly affecting the treatment protocols and care of the patient. Furthermore, a lack of consensus on the definition of fusion and/or an accepted quantitative measure of union ultimately hinders and devalues the broad spectrum of research on novel bone healing modalities.

The predicament is often overlooked within the literature where by a broad assessment of union without providing qualitative or quantitative parameters is routinely offered. This is perhaps a marginal improvement on those that forgo a definition altogether [4]. The problem however has not been completely ignored. There have been some elegant attempts especially within the orthopedic community to address this problem through a number of fusion measuring modalities. The goal of this paper is to review some of the current tools and options available for determining union within the orthopedic and podiatric literature and assess their application and validity to the lower extremity.

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The challenge of bone healing assessment has historically been undertaken either through imaging, clinical or mechanical evaluation. For clinical examination, the resolution of bone tenderness at the fracture site has been shown to be unreliable whereas radiographic validity continues to be questioned (a notion that will we explore later) [5,6]. This has lead some to explore the direct and in-direct mechanical measurement of union as arguable the most accurate form of bone healing assessment.

Mechanical: Biomechanical Tests

Richardson et al in 1994 adopted a biomechanical method to evaluate union based on a quantitative measure of bone stiffness [7]. He argued that stiffness of the fracture site is a good measure of healing as stiffness reflects both the increase in quantity and change in quality of repair tissues. His study looked at 219 pts with fracture of the tibial diaphysis that were managed with unilateral external fixation. One group (group1) had the external device removed when radiographic and clinical findings were suggestive of union (not elaborated). The other group (group 2), removal of ex-fix device was indicated when fracture stiffness was calculated to 15Nm/degree. The force (Nm) was measured by applying a manual load at a measured length proximal to the tibial fracture site. Angulation was measured either directly with flexible electrogoniometer (after ex-fix removal) or indirectly with a strain gauge unit applied to the fixator apparatus. The bending moment was then calculated as a ratio of the two values. Incidence of refracture was 7% in group 1 compared to 0% in group 2 suggesting that bending fracture stiffness of ≥15Nm/degree is a reliable indicator of early fracture union and a safe threshold to remove external fixation from tibial fractures. There are certain limitations however to this study, beyond the question of fibular contribution, its nature would not be applicable to internal fixation thus essentially excluding the majority of arthrodesis type fusions. Additionally this study does not extend beyond the evaluation of tibial fractures and thus such specific values cannot be applied as a standard throughout fractures of the lower extremity. Furthermore and as indicated by the author, a specific stiffness value to indicate bony union is potentially variable with parameters such as the weight of the patient and residual angulations of the fracture being influential factors. Presumably, one would also have to consider the potential detrimental effects of applying such a force to a fusion site especially in pedal cases where bone mass is relatively reduced.

Mechanical: Vibrational Test

Mechanical properties other than stiffness of healing bones have also been utilized. Vibrational testing has been voiced as a viable alternative that negates the requirement of manual manipulation. The principle is based on the work by Lippman and his study on the auscultatory percussion of fractured bones [8]. With use of a stethoscope and a percussing finger, Lippman noted that pitch and quality changes (compared to the contralateral side) result from free vibration of separate bone fragments and, accordingly, signify complete fracture or incomplete union. Furthermore appreciable diminution in sound intensity indicates poor conduction and reflects absence of end-to-end contact. With this, Fellinger in 1994 postulated that the sound signal of a knock impulse would therefore be perceived at both ends of a fracture with the same intensity if the sound transmission were not diminished by a fracture gap [9]. By using computerized analysis, Fellinger was able to quantify the changes in mechanical vibration reaction and acoustic sound transmission of tibial fractures (treated with an external fixator) and apply this as an evaluation of bone healing. This non-invasive, painless technique of computerized ultrasonometry has been shown (in animal studies) to have good correlation with quantitative CT measurements and microradiography, also it was shown to be able to detect early signs of delayed union before it was radiographically evident [9,10].

Despite this early promising work however, there has been little development in its application in the assessment of healing bones in vivo studies in humans. Regardless, it is difficult to see how this technology could be applied to scenarios of internal fixation, which essentially excludes our ability to physically measure the true extent of union. Of note, its application has however has been utilized as a measure of bone density, specifically within calcaneal quantitative ultrasonomtery for osteoporotic fractures and in the assessment of tarsal and metatarsal bones following reloading from a period of non-weight bearing [11,12].

Clinical

Its simplicity combined with the physicians natural inclination dictates that clinical assessment is the most utilized tool within bone union assessment. Ability to weight bare, pain on palpation and manual manipulation has become an integral part of post-operational review. However the practice suffers from a lack of clinical standardization rooted by the subjective nature of the assessment, a predicament highlighted by in 1996 by Web. Web leans on the work of Richardson and the concept of 15Nm/degree of stiffness as a reliable indicator for union [13]. The study uses a synthetic fracture model to examine the ability of orthopedic surgeons to assess the stiffness of a fracture manually. Surgeons were asked to estimate the stiffness of rods representing midshaft diaphyseal fractures at different stages of healing and confirm whether such stiffness equated to union or nonunion. They found that surgeons were unable to estimate the fracture stiffness accurately. On 83% of occasions when stiffness was less than 15Nm/degree, the surgeons considered the fracture models to be under union, concluding that manual testing of the mechanical stability of a fracture is unreliable. In addition, Coughlin in his work on evaluation of hindfoot arthrodesis found no correlation between clinical data (VAS, AOFAS scores) and the percentage of fusion via computed tomography [14]. Stating that such a lack of correlation prevents clinical measurements being used to define the radiographic threshold of fusion of hindfoot joints. Such studies facilitates in highlighting the difficulties and inadequacies of clinical assessment as a benchmark for union and further questions how any union assessment modality should be critically evaluated.

Imaging: Plain film radiographs

Plain film radiographs is the most common visual modality with a considerable number of studies using radiographic parameters as the sole basis of union determination. This perhaps can be largely attributed to ease to which one can obtain this visual aid within the clinical setting. Despite its ubiquitous nature however, a multitude of definitions without an accepted consensus for union (via radiographic assessment) exist within the literature. Bandhari et al highlighted this in 2002, with a provocative cross-sectional survey of 444 orthopedic surgeons in regards to tibia shaft fractures. His work showed significant discrepancies in the use of radiographic criteria for union determination as well as varying definition of non-union and mal-union [15].

Attempts towards an accepted unification of bone healing have however been made, of note Hammer et al used a combination of cortical continuity, absence of fracture line and callus scale to assess union [16]. The study evaluated 127 tibial shaft fractures by means of clinical assessment of fracture stability and compared this to radiographic assessment of union. Using this radiographic criteria, pts where placed into groups of achieved union, non-achieved union and uncertain. Each radiographic class was then compared to the mechanical class. Mechanical class was defined by deflection ratio, derived from the bending moment applied to the tibial and the measure of deflection that occurred at the distal fragment. He found that satisfactory union via radiographic interpretation was declared in 55% of clinically determined unstable fractures and that 44% of non-unions (via radiographs) were deemed mechanically stable. He thus concluded that conventional roentgenographic examinations as a means of assessing the stage of union are generally inconclusive and that radiographs should only be employed when clinical evaluation is proven unreliable. It is interesting to note that in Hammer's work, he makes the assumption that clinical evaluation and specifically mechanical stability is the gold standard for union, a concept that in it self is invalidated.

In a valiant attempt to generate standardization and limit variation in interobserver radiographic interpretation, Whelan developed systematic and quantitative way to assess fractures of the tibia [17]. This radiographic scoring system for tibial fractures (RUST) was greatly influenced by the work of Panjabi et al that showed that assessing the number of cortices bridged by callus as opposed to callus area is a strong predictor of union strength [18]. In Whelan's system, all four cortices are assessed (AP and Lat views) independently and scored from 1-3 based on the presence or absence of callus and visibility or invisibility of fracture line. Collectively a score from 4 (definitely not healed) to 12 (definitely healed) can be achieved. It is argued that the additive nature of this method allows one to assign an approximation as to the stage of fracture healing that has occurred; furthermore its systematic, simplistic form limits disparity in the interpretation of union. In his paper, Whelan used this method to assess 45 sets of tibial shaft fractures treated with intramedullary nails. To investigate the plausibility of interobserver agreement, seven independent reviewers of variable disciplines analyzed the radiograph and allocated a RUST score. Overall significant agreement was observed between the reviewers based on intraclass correlation coefficient (ICC) with 95% confidence intervals (ICC=0.86, 95% CI 0.79-0.91).

Despite positive reviews the RUST system has one notable limitation [19]. Do date; no application of the RUST scoring system has been applied to the foot. One would assume that this is primarily based on the fact that such a scoring system is based on the assessment of callus formation. Such formation is prominent in the IM fixation of tibial shaft fractures but actively inhibited within an ORIF mechanistic environment, a technique commonly adopted within the podiatric profession.

Imaging: CT (Computed tomography)

CT has been cited as superior to standard radiography in the assessment of union. Bhattacharya et al in 2006 investigated the diagnostic accuracy of CT in the assessment of bone healing of tibial fractures in 35 patients [20]. He considered that the clinical gold standard of fusion was union at time of surgery or after 6 months of clinical observation. In comparison to 2.5mm slice CT scans, Bhattavharya found very good diagnostic accuracy with CT assessment with a 100% sensitivity for detecting nonunion and an overall accuracy of 89.9%. Limitations however were noted with a low specificity (62%) as five patients with CT determined nonunion were found to have union.

The adopted radiographic protocol and the value of CT analysis have most recently been explored by Coughlin [14]. His prospective study looked at the progression of STJ or triple arthrodesis over a 12-month period assessed by serial CT (axial and coronal) and plain film radiographic (AP, LAT, Oblique and broden views) interpretation.

Fusion was considered when contiguous incorporation of graft or the presence of bridging bone was observed. Radiographically, this was then calculated to a percentage of fusion value based on the visualized portion of arthrodesis. A comparison measure of fusion was also calculated in the same manner with the accumulated percentage of sequential 2-mm CT slices of the 'fused' joint in the axial and coronal planes. The paper found that in most cases, radiographs overestimated the magnitude of joint fusion when compared to CT scans with poor agreement between the two modalities. Coughlin again highlights the ambiguity associated with the definition of successful fusion, citing numerous papers that use standard radiographs in the assessment of STJ and triple arthodesis without a criterion of evaluation.

Coughlin argues for a need to quantify the extent of fusion suggesting that fusion should be considered when >50% of bone bridging or graft incorporation is observed. This is based on his assertion that subtalar tarsal coalitions with 50% or more fusion (method of fusion is not divulged) and acceptable hindfoot alignment, typically do not require arthrodesis. Coughlin does however add that the percentage of fusion that defines successful arthrodesis remains to be properly determined. Indeed, Jones in his paper used CT scans to evaluate hindfoot non-unions following revision surgery and low intensity US stimulation [21]. To quantitative the extent of fusions, 1mm CT coronal cuts of the STJ and 1mm axial cuts of the CC and TN joints were evaluated. Fusion was defined as bone trabeculation or absence of lucency on each cut and measured using a digital caliper calculated by measuring the width of fusion and conveyed as a percentage of total bone healing. In this case he defined <33% as non-union 34%-66% as partial fusion and 67%-100% as complete union. Alternatively, Brinkers, in his paper on the use of lizarov compression for aseptic femoral non-unions defined union as bridging greater than 25% of cross sectional area of the non-union site, further highlighting the seemingly arbitrary nature fusion determination [22].

Conclusion

It is evident that the search for a universally accepted and validated approach to evaluating the progression of bone healing remains to be realized. The origin of the problem lies in the absence of an accepted gold standard for union, which in itself fuels and perpetuates the inability to assign a collective protocol and obligates one to suggest fundamental invalidity to the fashion of comparing one union assessing modality with another. Practically speaking and in regards to the foot and ankle, it is perhaps difficult however to look beyond the application of radiographic interpretation in combination with clinical assessment.

This is primarily due to its familiarity and accessibility within the field. However, such aforementioned problems have complicated its use and generated a plethora of invalidated criterion. In a systematic review of bone fracture care by Bhandari, the current definition of union and the reliability of the assessment of radiographic healing were explored [4]. Of 123 eligible articles, union was based on the combination of clinical and radiographic criteria 62% of time, solely on radiographic evaluation in 37% of the time and only clinical evaluation in 1% of the articles. Clinical criteria to define union primarily consisted of absence of pain/tenderness during weight bearing (49%), absence of pain/tenderness on palpation (39%) or ability to bear weight (18%). Plain film radiographic definition of bone healing consisted of observed bridging of the site by callus, trabeculae or bone (53%), bridging of the site by 3 cortices (27%) or cortical continuity (18%). The author comments that such an array of definitions for union within the current literature reflects the lack of consensus that exists within the orthopedic and indeed podiatric community.

Plain film radiographs remain the most common imaging modality in union assessment. It would therefore be prudent to suggest that future endeavors within the foot and ankle community would be most beneficial in exploring an accepted radiographic standardization protocol as has been seen with tibial fractures [17,19]. Such a system would potentially eliminate the unreliability of physician interpretation. Indeed, Coughlin found that fusion of hindfoot joints based on radiographs were overestimated by surgeons when compared to independent radiologist [14]. This therefore adheres perhaps to a system of radiologist interpretation (blinding) or more so to a method of quantitative measurement of union (as seen Coughlin's and Whelan's work) that removes the subjective nature of union interpretation.

It remains to be seen if such a protocol can be developed and validated for the foot and ankle. The persistent nature of union ambiguity may suggest that the complex interplay of biological pathways, mechanical forces in addition to patient variation are beyond the grasp of an imaging protocol.

As partly addressed, others methods of union determination have been investigated with varying degrees of acceptance, validity and potential application to the foot and ankle. This has been by no means encompassing, studies on serological markers for union pose great promise in this domain but are beyond the scope of this review [23]. Furthermore other imaging measures such ultrasound and PET scans have also been voiced as appropriate contenders [24,25]. However given the perceived reluctance to deviate from plain film radiographs, these modalities may best be suited within an adjunctive capacity.

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