Surgical Treatment Options in Patients With Impaired Bone Quality

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Published online: 8 March 2011
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Abstract

Background Bone quality should play an important role in decision-making for orthopaedic treatment options, implant selection, and affect ultimate surgical outcomes. The development of decision-making tools, currently typified by clinical guidelines, is highly dependent on the precise definition of the term(s) and the appropriate design of basic and clinical studies. This review was performed to determine the extent to which the issue of bone quality has been subjected to this type of process.

Questions/purposes We address the following issues: (1) current methods of clinically assessing bone quality; (2) emerging technologies; (3) how bone quality connects with surgical decision-making and the ultimate surgical outcome; and (4) gaps in knowledge that need to be closed to better characterize bone quality for more relevance to clinical decision-making.

Methods PubMed was used to identify selected papers relevant to our discussion. Additional sources were found using the references cited by identified papers.

Results Bone mineral density remains the most commonly validated clinical reference; however, it has had limited specificity for surgical decision-making. Other structural and geometric measures have not yet received enough study to provide definitive clinical applicability. A major gap remains between the basic research agenda for understanding bone quality and the transfer of these concepts to evidence-based practice.

Conclusions Basic bone quality needs better definition through the systematic study of emerging technologies that offer a more precise clinical characterization of bone. Collaboration between basic scientists and clinicians needs to improve to facilitate the development of key questions for sound clinical studies.

Introduction

Surgical management of orthopaedic conditions, from fracture repair to joint arthroplasty, is on the rise [18, 24, 74, 100]. The frequency of osteoporosis, and resultant fracture, is increasing worldwide [110]. The combination of increasing longevity, mobility, and severity of fractures secondary to poor bone quality presents a major challenge to surgeons who must choose the appropriate treatment option and select the optimal implant(s) to be used for fixation. Intuitively bone quality should be a touchstone for guiding this decision-making process. For example, the strength of threaded devices inserted into bone to support materials as diverse as sutures used in repairing avulsed tendons and spinal instrumentation is receiving increasing attention as these types of procedures are popularized. Because there is a proliferation of implant types and materials available, there would be a theoretical benefit to “individualizing” treatments if certain devices were found

One or more of the authors (NAJ) receives royalties from Exactech, Gainesville, FL.

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to improve immediate and long-term fixation in a particular degree of bone quality. The integration of bone quality into decision-making tools, currently typified by clinical guidelines, is highly dependent on precise terminology and the appropriate design of methodologically sound basic and clinical studies. It is important in deciding treatment options to understand the underlying basis of the poor bone quality.

This review was performed to determine the extent to which the issue of bone quality has been subjected to this type of process. This review addresses the following key questions: (1) What current methods of assessing bone quality are useful in clinical decision-making and what are their limitations? (2) What emerging technologies show potential clinical applicability? (3) What evidence connects bone quality with surgical decision-making in a selected group of commonly performed procedures, and how do such decisions relating to treatment options and implant selection in fracture fixation and reconstructive surgery affect the ultimate outcome? In the context of these questions, we explore what gaps in knowledge need to be closed to better characterize bone quality for the purpose of making it more relevant for clinical treatment decision = making.

Methods

We used the PubMed search engine to identify papers relevant to these questions. Additional sources were found using the references cited by identified papers. Our aim was not to produce an exhaustive, systematic review of each of the questions posed, but rather to use the existing literature to synthesize an assessment of the current status of bone quality in relationship to preoperative planning and to make recommendations when possible.

Current Assessment of Bone Quality: State of the Art

Bone quality is a term that has become widely used to describe the aspects of bone that affect its ability to resist fracture [14, 52]. These include bone's structural (eg, geometry and microarchitecture) and material (eg, mineral and collagen composition) properties at multiple hierarchical levels of organization [33, 52]. In clinical contexts, bone quality is often considered to refer to all factors affecting fracture that are not accounted for by bone mass (eg, bone mineral density [BMD] as determined by dual-energy xray absorptiometry [DXA]) [17, 141]. Unfortunately, there is terminologic confusion in the clinical literature and sometimes measures of BMD are used interchangeably with bone quality, whereas other times

they are separated. Because BMD is largely a measure of bone mass, it incorporates information to some degree on bone mineralization, porosity, and cross-sectional size [119]. Therefore, it is impossible to consider it completely separate from bone quality. For this reason as well owing to limitations of existing clinical assessment methods, our review uses the term "bone quality" in a wider sense, incorporating BMD. Throughout this review, we specify which measure of bone's structural, geometric, or densitometric properties is being used.

The assessment of bone quality depends on imaging modalities for the purpose of a practical definition and clinical application. Although many techniques are available for in vivo and ex vivo assessment of bone quality, as reviewed in other articles in this symposium, the following section focuses on those routinely used for assessing bone quality in clinical, preoperative settings.

Radiographs

Radiographic methods, although two-dimensional and of limited resolution, can provide site-specific information on bone structure and shape in cases of arthritis or fracture. This can be done efficiently and at relatively low cost [93]. The Singh Index (SI) reportedly correlates with bone biomechanical properties [21, 72, 139] and thus used to classify osteoporosis severity in the proximal femur [120]. However, it has been criticized for being subjective [72], and some studies show poor correlations with DXA-determined BMD [55, 112]. The Dorr classification system [26] is used to classify proximal femur geometry based on measures of the canal-to-calcar ratio and cortical thickness index, resulting in the classification of bones into three types (A, B, and C) [26]. Cortical thickness index shows the best correlation of all of the Dorr parameters with BMD [112].

Dual-energy Xray Absorptiometry

DXA-determined BMD has been used to define osteoporosis (through the use of T-scores) [142], predicts fracture risk [20, 92], and can monitor response to therapeutic interventions [11, 64]. Although DXA provides only limited information on bone quality beyond a two-dimensional measure of bone mass, it is the most widely accepted clinical assessment method and along with radiography is often the only measure available. Hip structure analysis (HSA) was developed to assess two-dimensional geometric properties from DXA images [27, 90], but whether this improves the ability to predict fracture risk remains unclear [12, 129].

Computed Tomography

CT can be used clinically for delineating intraoperative and postoperative fractures, templating for complex reconstruction [76], and volumetric imaging of osteolytic lesions [32], although its use is not routine and is limited in patients who already have metallic hardware [117]. Quantitative CT (QCT) allows for separate assessment of cortical and trabecular bone density and geometry. Its *in vivo* use has been limited to peripheral sites (pQCT) such as the distal radius and tibia where it has potential as a diagnostic tool [13] or for monitoring response to therapies [113]. Newer methodologies using fewer CT slices [104, 118] may allow QCT to become a feasible clinical tool for pre- and postsurgical evaluation.

Emerging Technology

Ideally, the ability to obtain detailed information about bone quality at its microarchitectural level would be feasible in a clinical setting. Most currently available high-resolution imaging modalities are limited to *ex vivo* research use as a result of radiation levels and sample size/acquisition time limitations [37]. High-resolution computed tomography (hrQCT) and high-resolution MR (hrMR) can be performed *in vivo*, although to date the techniques have largely been used to validate the technologies and assess the efficacy of osteoporotic therapies. Recent applications of these technologies for preoperative and postoperative assessment have been reported [104, 118], and the potential for more routine clinical use exists [66]. These technologies, when used in combination with biomechanical testing and/or finite element (FE) modeling [63], and correlated to other *in vitro* high-resolution techniques such as histology, microcomputed tomography (μ CT), and micromagnetic resonance (μ MR) [38], may eventually facilitate a more precise and accurate assessment of bone quality [37, 94] with the potential for identifying surgical risk factors associated with poor bone quality.

Does Bone Quality Affect Surgical Decision-making?

Spine Surgery

The incidence of spinal surgery using instrumentation has steadily increased over the last two decades [24]. As elderly patients continue to demand a high level of daily function, spine surgery will likely be performed more frequently in patients with suboptimal bone quality [22, 35], including those with degenerative spondylolisthesis [71] and scoliosis [22].

Biomechanical evaluations of cervical [106, 146], posterior thoracolumbar pedicle [16, 46, 48, 126, 144], and anterior thoracolumbar screws [31, 79, 80, 123] demonstrate linear variation among DXA-based bone density, insertional torque, and pullout strength. Studies using QCT [31] have also demonstrated a relationship between spinal instrumentation and cortical and cancellous bone density. It remains unclear how relevant these biomechanical studies are to clinical results. Not all physiological aspects of the spine-implant construct can be reproduced in a cadaver, particularly the stability conferred by the spinal musculature and the thoracic cage and the polyaxial forces on the spine during physiological activity.

In vivo studies evaluating this relationship are few in number and have reported varying results, from a higher rate of pseudarthrosis and screw loosening in patients with osteoporosis [99] to no relationship [73]. A potential explanation for this variation may be the exclusion of patients with radiographically severe osteoporosis in some studies but not others. On balance, both biomechanical and clinical studies suggest low BMD as determined by DXA [80, 99], or plain radiography [35, 126], and sometimes by QCT [31, 123, 146] may lead to increased pseudarthrosis and screw loosening using a variety of types of spinal instrumentation.

Careful preoperative evaluation and planning can help to prevent pseudarthrosis and screw loosening. For example, using a screw tap for pilot hole preparation decreases the pullout strength of the screw [16], although this can be partially mitigated by using an undersized tap [48] or instilling polymethylmethacrylate bone cement after pilot hole preparation [126]. In addition, the technique of screw insertion can be altered to maximize screw fixation [7, 47, 111, 122]; for example, directing pedicle screws toward and penetrating the midanterior cortex where optimal bone strength is seen [111, 122] or placement of screws in a convergent, triangulated fashion to increase the resistance to pullout in the osteoporotic spine [7, 47]. Furthermore, use of a staple to support an anterior thoracolumbar screw increases the pullout strength of the screw [123]. Finally, postoperative bracing may also provide added stability [146].

Most surgeons, however, are not obtaining bone density data preoperatively [25]. A recent survey found that only 44% of surgeons ordered preoperative DXA scans before performing instrumented fusions, although 74% of those who did obtain such data reported using this information to alter their treatment or surgical plans.

Hip Arthroplasty

Cemented femoral stems have been considered by many to be the gold standard for THA because of documented long-term durability for up to 30 years [145]. However, patients

with atrophic arthritis, a history of fragility fracture, narrower femoral cortices, and lower periprosthetic BMD are more likely to have loosening of these stems [96].

Followup studies of cementless stems have demonstrated uniformly low mechanical failure rates for all types of bone quality based on the Dorr radiographic classification system [67, 87, 91]. However, the mere existence of a wide variety of cementless femoral stem designs is indicative of the diversity of implant designers' approaches to optimizing the mechanical and physiological environment of the proximal femur. The internal contours of the femur are complex and varied [97]. The introduction of a femoral stem will substantially change the endosteal loading environment with the natural tendency of an intramedullary stem to transfer load distally because of its relative stiffness. Modifications of size and geometry proximally and distally may substantially change this load distribution [34, 41, 54, 75].

Standardized radiographic views are routinely used in conjunction with preoperative templating for implant selection [97]. Although these techniques may be useful for predicting implant size, position, and alignment [43], variations in patient positioning may affect the radiographic projection of the proximal femur and alter the accuracy canal dimension measurements [28, 70, 137]. Supplementing preoperative templates with intraoperative radiographs [28] and other visual and tactile cues as the surgery proceeds [137] may improve the precision and accuracy of implant sizing. Computerized simulations may also be helpful [76, 98].

Femoral stem geometry is designed to optimize load distribution; however, the individual variations of native proximal femoral morphology ultimately determine the location and size of the contact zones. For example, if a tubular stem is used in a Dorr Type A femur, with a low canal-calcus ratio and high cortical index, there would be a tendency for increased diaphyseal stress concentration and proximal stress shielding. In the case of Dorr Type C bone with a high canal-calcus ratio and low cortical index, the use of a tapered stem would be more likely to lead to excessively high proximal loads and limited distal contact [54]. Therefore, it may be beneficial to individualize femoral stem selection in extreme cases. However, there is no evidence that has clearly shown any one bone type to represent an absolute contraindication for the use of any particular stem design [67].

Periprosthetic BMD, usually measured with DXA, has been followed over time to study the bony response to the implantation of a femoral stem [60]. In general, there is a preferential loss of proximal bone density during the first 6 months with varying patterns of partial recovery or continued slow loss of density over the longer term. Although proximal stress shielding with bone atrophy has been reported with distal-fitting chrome-cobalt stems, there has

been no demonstration of the impact of postoperative bone loss on pain, function, or prosthetic survival [15]. However, because marked localized periprosthetic bone loss may have long-term implications related to the difficulty of performing revision surgery, it may be best to avoid such extreme loading mismatches. Attempts to more precisely match the size and shape of the implant to the bone have not demonstrated the expected improvement of long-term fixation. Although customized femoral stems have been observed to effectively preserve proximal femoral BMD [60], the high degree of femoral canal fill has not prevented loosening and has resulted in ultimate failure at unacceptable rates [84]. This approach has been widely abandoned.

Because of the difficulties of assessing the periarticular bone of the acetabulum with plain radiographs, few studies have examined the effect of acetabular bone quality on THA. Moreover, cementless technology has improved the reliability of acetabular fixation to the point where bone quality is not regarded as an important issue in the vast majority of cases [36, 56, 57]. However, preoperative assessment and intraoperative awareness of acetabular bone quality may help to prevent important technical errors that may negatively affect long-term bone support and fixation. When THA is performed for inflammatory arthritis and for hip fracture, the subchondral cancellous bone may be extremely porous. This may signal the need for a careful approach to reaming so as to avoid a complete breach of the subchondral plate. However, there is no evidence to suggest preoperative acetabular bone quality predicts the long-term fixation for cementless fixation.

Considerations of bone quality in revision THA have mainly to do with the size and location of osteolytic defects and defects or fractures created during implant removal. Several classification systems for measuring the degree of bone loss and predicting technical difficulty have been devised [23, 61, 88]. For the most part, the classification systems are based on evaluation of plain radiographic images. However, CT assessment of the size of osteolytic lesions is particularly useful on the acetabular side, where substantial lesions may be shielded from view by the acetabular component [29]. The evaluation of the many different approaches to management of bone loss in revision surgery is beyond the scope of this review. Any direct correlation between bone loss and surgical outcome is difficult to assess because of the wide diversity of types of bone loss, the limited reproducibility of most classification systems, and the nonstandardized treatment alternatives [61, 88].

Knee Arthroplasty

Substantial BMD losses in the tibial metaphysis have been reported in longitudinal studies of multiple knee designs

with a preference noted for higher loss of cancellous than cortical bone [95]. Cemented TKA alters the BMD of the proximal tibia postoperatively [124]. Alternative designs have been suggested to reduce this bone loss, [85]; however, there is no evidence that conclusively distinguishes any one design as more bone-conservative. Even in rheumatoid arthritis, a worst case scenario for preoperative bone quality, there is no evidence for higher loosening rates for cemented all-polyethylene tibial components [127].

A similar lack of differentiation is seen with cementless TKA. Although some influence of low BMD on early migration of the uncemented tibial implant has been reported [77], there is no evidence that lower BMD influences long-term tibial component loosening or migration [5, 77, 130, 131, 138]. Furthermore, apparently no differences in BMD loss occur between cemented and cementless stemmed tibial components [1].

The bone loss that is typically seen during revision TKA may be a result of patient age, gender, comorbidity, stress shielding, osteolysis, and the mechanical (destructive) effects of implant removal. Reconstructive challenges primarily relate to an accurate preoperative and intraoperative assessment of the location and severity of bone loss [105]. The integrity of the metaphyseal bone envelope and diaphyseal cortical integrity must be assessed independently. Technical considerations including proper stem length and diameter, augment size, methods for filling massive bone defects, and optimal fixation methods are the major considerations in this situation [4, 86, 105].

Periprosthetic fractures after hip and knee arthroplasty are believed to relate at least in part to BMD, although the actual risk may be determined by a more complex interaction of multiple factors [45, 81, 82]. Cadaver-based biomechanical studies have found proximal and distal femur BMD, age, cortical thickness, and body mass index all correlate with load to failure [59, 116]. The use of cement in patients with compromised bone quality may have an “internal stiffening” effect on the femoral canal and therefore decrease the risk of periprosthetic fracture [59, 132].

Developing a rational treatment strategy for periprosthetic fractures is further complicated by the limitations imposed by various classification systems for periprosthetic fractures, which are not necessarily standardized or validated and do not adequately characterize bone quality. Early classification systems for periprosthetic fractures in TKA focused exclusively on the fracture pattern (displaced versus nondisplaced) and the fixation of the prosthetic components (stable versus loose) [108]. Treatment options were then limited by a restricted selection of fixation devices and prosthetic implants. Contemporary fracture classifications have added bone quality as a consideration

to differentiate those fractures that may be treated with open reduction internal fixation or by using a revision prosthesis with stems from those with unacceptably poor quality requiring a distal femoral allograft or prosthetic replacement of the entire distal femur [49, 62, 68]. Fracture fixation technology has been substantially improved by the development of locking plates, locked intramedullary rods, and more user-friendly, graded prosthetic replacement options. However, the comparison of the results of various reconstructive strategies remains difficult because the grading of bone quality remains largely subjective and treatment options are not fully standardized.

Rotator Cuff Repair

The bone quality of the proximal humerus (greater tuberosity specifically) has been believed to be a relevant factor in determining the strength of fixation of suture anchors used for rotator cuff repair [8, 39, 109] along with tendon quality and tendon-grasping technique [6, 39, 65]. Higher rotator cuff rupture and failure rates have been clinically observed in osteoporotic bone [50] as determined by DXA. Although biomechanical studies find no relationship between DXA-determined BMD and metal anchor pullout or failure [6, 44], CT-based measures (QCT and hrQCT) demonstrate variations in trabecular bone density and quality that correlate with failure load of various tested anchors [69, 102, 133, 135].

Because of the increasing use of arthroscopic rotator cuff repair with suture anchors, there has been considerable debate regarding the optimal anchor placement in the greater tuberosity (proximal or distal, anterior or posterior). QCT [135] and HR-pQCT [69] studies have identified a positive relationship between density and load to failure within the greater tuberosity with the highest values for both within the proximal part of the tuberosity relative to the distal region. The exact pattern of variability in this relationship within the proximal region differs between studies, possibly as a result of the differences in the regions of interest chosen as well as potential limitations of QCT to assess BMD accurately in small volumes.

Anchor design may also be important in the prevention of anchor loosening [102, 133]. Metallic screw-in anchors [103, 133] and subcortical wedging anchors [103] have a higher mechanical pullout strength than other anchor types. Despite the development of anchors made of new bioabsorbable materials, the anchor type rather than material is likely to be the more important determining pullout strength [102].

The pattern of the individual rotator cuff tear (size and amount of retraction) and the surgeon's ability to mobilize the tear are major determinants of the strength of the repair.

Within those constraints and based on the noted bone quality variations, we recommend that suture anchors be placed in the proximal part of the greater tuberosity. The literature remains inconclusive regarding anterior versus posterior placement and does not demonstrate superiority of either metal or bioabsorbable anchors.

Fracture Fixation and Repair

Little is known about the relationship between bone quality and the strength of internal fixation in the proximal humerus. DXA-based studies are inconclusive [143], whereas QCT does show correlations between proximal cortical thickness and BMD and BMD and screw pullout strength [134, 136]. Regionally, the central zone of the humeral head has the highest BMD and generates the highest pullout strength. We therefore recommend that fixation screws be placed at or around the center of the humeral head [136].

The use of fracture fixation devices versus hemiarthroplasty in patients with poor proximal humeral bone quality remains controversial. Although better pain, power, and mobility have been observed with the use of the locked plate in osteoporotic patients [125], some studies caution that locked screw plates in osteopenic patients are associated with high complication risk and therefore are not superior to prosthetic replacement [19]. Although numerous biomechanical, cadaver studies have also supported the use of locking plates, particularly in complex fractures or in bone with poor quality [40, 140], clinical studies comparing fixation techniques in bone of varying density or quality in the proximal humerus are lacking (although a recent study has been reported for distal humeral fractures [115]). There is also a lack of comparative studies that include nonoperative treatment as a potentially valid option [107].

Fractures of the femoral neck pose a major public health problem [30], and internal fixation has been associated with an unacceptable reoperation rate of up to 48.8% [9, 89]. It would be natural, as many arthroplasty surgeons have done, to virtually abandon this procedure in favor of either hemiarthroplasty or THA. In a recent survey of members of the American Association of Hip and Knee Surgeons regarding treatment preferences for displaced femoral neck fractures, only 2% of respondents reported using cannulated screws for patients older than 65 years old [58]. However, another survey conducted among predominantly trauma fellowship-trained surgeons (73%) demonstrated an 11% (Garden IV) and 25% (Garden III) preference for internal fixation in patients from 60 to 80 years old [10]. There was considerable variation regarding the type of implant used for internal fixation.

It has been generally accepted that bone quality is at least partly responsible for enhancing the stability of fixation and the overall potential for fracture healing. Biomechanical studies in cadavers show positive correlations between measures of proximal femoral density and fracture fixation [121, 128]. However, clinical studies have not been definitive in establishing bone quality as a critical factor. In one prospective multicenter study, no difference was found in revision to arthroplasty rates in osteoporotic and osteopenic patients treated with a variety of fixation methods [51]. In another, older age was one of several factors influencing variability in fixation failure, suggesting a possible role of bone quality [147]. In summary, although age, bone quality, and type of fixation device used may relate to the strength of fixation and healing potential in femoral neck fractures, the relative importance of each of those factors has not been clearly demonstrated.

The relationship between bone quality and fixation of tibial plateau fractures has also been investigated. At this site, poor bone quality associated with osteoporosis and older age are associated with increased comminution of tibial plateau fractures, increased fracture depression, and compromised or failed fracture fixation [53, 114]. Low BMD has been correlated with higher fixation failure rates in both clinical and cadaveric studies [2, 3]. The impact seems to be less with external fixation than with dual plating, suggesting external fixation may be a more attractive alternative in the elderly patient [3]. Despite the potential role for DXA and pQCT in surgical decision-making [3], a validated treatment algorithm based on proximal tibial bone quality has not yet been constructed.

The distal radius has been extensively studied because of its manageable size, easy accessibility, and the fact that it is widely regarded as a sentinel for increased risk for osteoporotic fractures in other locations [101]. Using DXA and pQCT to characterize the amount of bone and its geometry, substantial advances have been made in developing more accurate clinical methods of determining radial strength and the risk of fracture. In fact, because it is a site that is readily imaged in vivo with high-resolution methods such as HR-pQCT [83] and hrMRI, it is a location where tissue level bone quality data can be obtained. There is ample evidence that reduced BMD, poor geometry, and QCT bone quality correlate with fracture risk [101] and with higher-grade fracture using several different classification systems [78]. However, once a distal radius fracture has occurred, the specific characteristics of the fracture do not necessarily drive an evidence-based set of treatment options. In December 2009, the American Academy of Orthopaedic Surgeons (AAOS) approved “The Treatment of Distal Radius Fractures: Guideline and Evidence Report” (<http://www.aaos.org/guidelines>). In this report, the AAOS was unable to provide any recommendations for

or against various fixation methods, operative treatments, or locking plates for distal radius fractures in patients older than age 55 years. Even at the most basic level, they were unable to recommend for or against using the occurrence of distal radius fractures to predict future fragility fractures, citing a lack of evidence as the major factor in the weakness of the recommendations as well as a need for inclusive research to more clearly specify subgroups according to levels of activity, age, comorbidity, and patient expectations. They also advocated for further evaluation of adjuvant bone grafts in association with the use of locking plates in elderly and sedentary patients. Conspicuous by its absence, however, was any specific mention of the need to routinely evaluate bone quality except in its association with a recommendation for the re-evaluation of the assumed relationship between low-energy distal radius fractures and osteoporosis. A recent systematic review focusing on proximal humerus, distal radius, and hip fracture similarly cited a lack of evidence demonstrating an influence of osteoporosis on fracture fixation [42]. The review pointed to a lack of prospective clinical studies aimed at elucidating this relationship, attributable in part to a lack of accurate methods of osteoporosis assessment and inconsistent definitions of complications.

Discussion

The objective of this study was to assess the clinical relevance of current concepts of bone quality from the standpoint of risk for surgical failure in multiple commonly performed procedures. We reviewed current and developing imaging modalities and discussed the basic and clinical evidence available to connect bone quality with approaches to fracture fixation, implant selection, and improved clinical outcomes for a variety of commonly used surgical procedures. In this context, we aimed to identify the gaps in knowledge that need to be closed to better characterize bone quality clinically and use such information for making evidence-based treatment decisions.

We recognize limitations of our survey. First, we approached our review using the term “bone quality” in a loose sense, incorporating DXA-based BMD measures, which are often the only available measures of bone status to correlate with bone strength. Given that our review is based on data that necessarily derive from these limited sources, we cannot elucidate nor separate which aspects of bone quality can best aid in surgical planning. Second, we performed a selective review relying primarily on PubMed as our search engine and did not provide the reader with our inclusion criteria. We likely did not identify every relevant paper, and it is possible that some papers not included could have provided insight into our questions.

Our review of current methods for assessing bone quality preoperatively suggests there are major challenges to the classification of bone quality and determining its contribution to standardized evidence-based treatment decisions. Among the reasons for this is the widespread reliance on relatively crude estimates using plain xray and DXA-determined BMD [77, 96, 99, 131]. There is a need to design cadaver-based biomechanical studies to correlate between what is available clinically (BMD) and more definitive studies using histology and high-resolution three-dimensional imaging. Our review of emergent technologies suggests those techniques that are hierarchical and correlative between length scales and incorporate measures of performance using μ -finite element analysis may lead to new breakthroughs in this area [94]. As a more integrated picture of the microstructure and geometry of bone emerges, it is likely the information will gain clinical relevance. Until then, a major gap remains between the basic research agenda for understanding bone quality and the transfer of these concepts to evidence-based practice.

Cadaver-based biomechanical studies do offer compelling evidence for a relationship between bone quality and approaches to fracture fixation [3, 135, 136], instrumentation [48, 122, 126, 146], and rotator cuff repair [69, 102]. The paucity of clinical studies, and their limited ability to adequately assess bone quality, limits the prospect for evidence-based treatment recommendations. Prospective clinical studies, designed to address these relationships and using more carefully defined measures of bone quality, are needed. Unfortunately, even at sites such as the distal radius where the potential for high-resolution imaging may provide clinically relevant data on bone quality sooner than at more proximal locations such as the hip and spine, there does not appear to be a great deal of optimism for this prospect. The AAOS guidelines for the treatment of distal radius fractures, based on a systematic literature review, do not include a more comprehensive understanding of bone quality as an important research priority. For the many who are working toward this end, a call to action should be sounded. A more comprehensive definition of bone quality, systematic study of emerging technologies for more precise clinical characterization of bone, and improved collaboration between basic scientists and clinicians is needed.

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