ISSN-E: 2737-6439
Athenea Journal
Vol.3, Núm. 10, (pp. 16-29)

https://doi.org/10.47460/athenea.v3i10.45

# Review-Bone Characterization: Mechanical Properties Based on Non-Destructive Techniques

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Recibido(12/03/2022), Aceptado(05/06/2022)

**Abstract:** This paper characterizes the state of art in the mechanical properties of bone and seeks new avenues aligned with non-invasive characterizations to better fit and produce innovative technologies within the biomedical implant field and early detection of bone diseases. It is concluded that the combination of these methods and non-invasive techniques contributes significantly to obtain the mechanical properties of the bones, which could be extremely useful in the early detection of bone diseases, developing biological models, and performing mechanical analysis with the intent to predict abnormal biological behaviors in human beings.

Keywords: bone, non-Invasive techniques, mechanical properties, biomaterials.

## Caracterización de Huesos: Propiedades Mecánicas Basadas en Técnicas No-Destructivas

**Resumen:** Este artículo caracteriza el estado del arte en las propiedades mecánicas del hueso y busca nuevas avenidas las cuales estén alineadas con caracterizaciones no invasivas para que así se puedan adaptarse mejor y producir tecnologías de vanguardia dentro del campo de implantes biomédicos y detección temprana de enfermedades en los huesos. Se concluye que la combinación de estos métodos y técnicas no invasivas contribuye significativamente a obtener las propiedades mecánicas de los huesos, lo cuales pudieran ser de gran utilidad para la detección temprana de enfermedades óseas, el desarrollo de modelos biológicos y la realización de análisis mecánicos con la intención de predecir comportamientos biológicos anormales en los seres humanos.

**Palabras Clave:** hueso, técnicas no-invasivas, propiedades mecánicas, biomateriales.

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## I. INTRODUCTION.

The field of prosthetics operates under largely empirical knowledge. Artificial limbs are expensive, but without a proper fit, these high-tech appendages are worthless—a poorly attached prosthesis is not just uncomfortable and painful, it can also further injure a patient and create another type of problems for their skin and musculoskeletal system discussed on [1]. Today, state-of-the-art prosthetics are mechanical limbs controlled by nerve impulses and microprocessors. While these enhancements can make life easier for amputees, a cutting-edge limb alone will not suffice, they must fit properly. A high-tech limb with an unsecured interface can fall off or cause unnecessary energy loss between a living limb and artificial extension. To ensure a perfect fit, patients need to go for multiple moldings, and they require routine adjustments. But even with all the expense and effort put into a good fit, most of the time limbs are attached with simple suction or skin traction presented on [2]. There are several options that could avoid these types of problems, and in particular, a method that uses biomaterials would allow for tried and validated applications.

Osseointegration, the process of surgically grafting an artificial limb onto a living bone as indicated in [3], ensures the greatest energy transfer and fit between the body and the prosthesis. A limb is attached over two surgeries. During the first procedure, a titanium screw is inserted into the marrow of the residual limb. Several months later, when this screw has become successfully integrated into the bone, doctors add an extension to which the prosthesis will attach.

This process would use engineered materials in its application. The integration of these materials necessitates a way in which the patient can be evaluated non-invasively, and a procedure or plan can be formulated and tailored to the individual. This would require streamlining the process to a few points of data from which the plan for the prosthetic is generated. These consist of the engineering mechanics of bones and joints, the physical characteristics of the patient, the kind of use the prosthetic will have, and the life of the product desired. While some of these details can be answered on a questionnaire, others need to be obtained through observation. An important part of this process is to neither hurt the musculoskeletal nor the skin of the patient, so this necessitates a non-invasive method of collecting data about bones and joints. This would allow us to calculate, using known engineering characteristics of bone, a near as possible perfect implementation of osseointegration.

## II. FIELDS OF INTEREST TO THE SUBJECT

### *A. A Brief Review: Biomaterials*

This review discusses the factors important in the incorporation or integration of biomaterials and devices by tissue. Methods for surface modification and surface-sensitive techniques for analysis are cited. In vitro methods to evaluate the biocompatibility or efficacy of certain biomaterials and devices are presented in [4]. Present and future directions in neural prostheses, cardiovascular materials, blood or bone substitutes, controlled drug delivery, orthopedic prostheses, dental materials, artificial organs, plasma and cytopheresis, and dialysis are discussed in [5], [6].

### *B. Characterization of Bone Material Properties and Microstructure in Osteogenesis Imperfect / Brittle Bone Disease*

Nanoindentation was used to examine the longitudinal elastic modulus and hardness at the material level for mild Osteogenesis Imperfect (OI) type I vs. severe OI type III. Both modulus and hardness were significantly higher (by 7% and 8%, respectively) in mild OI cortical bone compared to the more severe phenotype. Lamellar microstructure also affected these properties, as the younger bone material immediately surrounding osteons showed decreased modulus (13%) and hardness (11%) compared to the older interstitial material seen in [7].

A high-resolution micro-computed tomography system utilizing synchrotron radiation (SRμCT) was described and used to analyze the microscale vascular porosity, osteocyte lacunar morphometry, and bone mineral density in OI vs. healthy individuals. Vascular porosity, canal diameter, and osteocyte lacunar density were all two to six times higher in OI cortical bone. Osteocytes were also more spherical in shape.

Finally, three-point bending techniques were used to evaluate the microscale mechanical properties of OI cortical bone in two different orientations. Elastic modulus, flexural yield strength, ultimate strength, and crack-growth toughness were three to six times higher in specimens whose pore structure was primarily oriented parallel vs. perpendicular to the long bone axis. There was also a strong negative correlation between the elevated vascular porosity of OI cortical bone and its elastic modulus, flexural yield strength, and ultimate strength. This relationship was independent of osteocyte lacunar density and tissue mineral density.

In summary, these findings highlight new material and microstructural changes within OI cortical bone that help contribute to its fragility. They also underscore a deep connection between bone structure and mechanical integrity at multiple length scales.

### *B. Predicting regional variations in trabecular bone mechanical properties within the human proximal tibia using MR imaging*

Recent studies have shown that high-resolution magnetic resonance (MR) imaging allows 3D characterization of bone microstructure. Using MR, whole joint images may be acquired with details of both bone and the surrounding soft tissue. While MR is not able to measure the amount of minerals in the bone as determined in X-ray-based imaging modalities that measure bone mineral density (BMD), it is possible to distinguish between bone and bone marrow to determine bone volume fraction. Correlations between the amount of bone and Young's modulus, yield stress, and ultimate stress have been determined using MR and several other clinical and experimental imaging modalities. Along with the amount of bone, it has been reported that trabecular bone orientation and structure contribute to bone strength based on [8].

### *C. Bone Characterization using Piezotransducers as Biomedical Sensors*

This technical note explores the possibility of miniaturized piezoelectric ceramic transducers (PZT) patches as biomedical sensors to evaluate the structural dynamic characteristics of bones, by employing them as transmitters and receptors of acoustic waves. The results show that theoretical computations are not very reliable for bone-like materials, but the results, in general, are enough to warrant more study as a method of detecting imperfections such as bone porosity rather than structural characteristics according to [9].

### *D. Nanomechanical characterization of tissue-engineered on bone grown on titanium alloy in vitro*

In this study, the bone-like mineralized matrix was produced by osteoblasts cultured in vitro on the surface of titanium alloys. The volume of this tissue-engineered bone is so small that the conventional tensile tests or bending tests are implausible. Therefore, nanoindentation techniques that allow the characterization of the test material from the nanoscale to the microscale were adopted. These reveal the apparent elastic modulus and hardness of the calcospherulite crystals (a representative element for woven bone). Nanoindentation with in situ atomic force microscope (AFM) imaging is very useful to identify and characterize the small features in the bone which is not easily achievable by other techniques. The surface topography of sub-regions, heterogeneous microstructure, anisotropy (local grain orientation), and inhomogeneous composition lead to a statistical distribution of the measured Young’s modulus and hardness. The average value of Young’s modulus is consistent with what is expected for woven bone in a rat. The hardness values are also reasonable for this type of bone. Dynamic mechanical analysis during nanoindentation can determine the viscoelastic properties of this tissue-engineered bone as indicated in [10].

### *F. The Mechanical Properties of Bone*

Comparison of the maximum compressive stress and modulus of elasticity of the rectangular and cubic specimens according to the direction of loading showed that spongy bone is an anisotropic material, i.e., a material that is not equally strong in all directions. Another mechanical property of bone to be considered is its fatigue life. This is especially important about march, stress, or fatigue fractures debated in [11].

### *G. Biomechanical Characteristics of the Bone*

A hard material will respond with a minimum deformation to the load increase. When the material fails at the end of the elastic phase, it is considered a fragile material. Glass is an example of a fragile material. The bone is not so hard as glass or metal, and the difference between the materials is that it does not respond linearly, because it cedes and deforms, but not uniformly during the load placement phase. The higher the load imposed on the bone, the higher the deformation. In addition, if the load exceeds the elastic limits of the material, there will be a permanent deformation and failure of the material. If a material continues to over-elongate and over-deform in the plastic phase, it is known as a flexible material. The skin is an example of a material that is deformed considerably before the failure. Bone is a material that has properties that respond in both the fragile and the flexible mode as reported in [12]. This article indicates that the hardness of the bone is a good indicator of its mechanical properties. It also suggests porosity as affecting the hardness of bone, as materials science tells us does with other materials.

### *H. Bone Mechanics*

The field of bone mechanics has evolved to a very sophisticated level, in which the mechanical properties of cortical and trabecular bone are available for many anatomic sites. Studies have reported on the effects of bone density, aging, and disease on these properties, enabling researchers to perform highly detailed specimen-specific analyses on whole bone and bone-implant systems mentioned in [13]. This article suggests that current methods of measuring porosity (really bone density) would be useful in determining an individual's bone mechanical properties against a standardized set of data.

### *I. The Material Properties of Human Tibia Cortical Bone in Tension and Compression: Implications for the Tibia Index*

The properties of bone are subjected to a more precise standard of measurement and the difference in precision is found to have yielded no statistically significant difference from other less precise experiments established in [14]. From this we take that observation from a patient can be interpreted from a less invasive test with comparable results to the most invasive test of all, dissection, and preparation for a stress-strain test.

### *J. Noninvasive Measurements of Bone Mass, Structure, and Strength: Current Methods and Experimental Techniques*

The article presents different types of radiological procedures that would allow for non-invasive measurement of bones that are evaluated to be very promising and in need of validation. Based on [15], the noninvasive technics used for assessing bone content and density are dual-photon absorptiometry single-photon absorptiometry, dual-energy X-ray absorptiometry, and quantitative computed tomography (QCT) while distinguishing between patients with and without osteoporosis. Extensions of conventional densitometry have been developed by several researchers to include information related to bone mass also are presented. Preliminary studies show the values of these new techniques in the noninvasive measurement of bone structure to estimate the bone strength and assess fracture risk more accurately.

### *K. Measurement of abnormal bone composition in vivo using noninvasive Raman spectroscopy*

X-ray-based diagnostic techniques are by far the most widely used for diagnosing bone disorders and diseases, which are largely blind to the protein component of bone. Bone proteins are important because they determine certain mechanical properties of bone and changes in the proteins have been associated with several bone diseases explained in [16]. Spatially Offset Raman Spectroscopy (SORS) is a chemically specific analytical technique that can be used to retrieve information noninvasively from both the mineral and protein phases of the bone material in vivo.

The protein composition of bone is an indicator of porosity thus it could be linked to the strength of the material if compared to an established set of data.

### *L. Osseointegration: An Update*

Osseointegration is a complex process between an implant and the bone surrounding it that can be influenced by many factors relating to the surface topography, biocompatibility, and loading conditions all play an important role in osseointegration. The quality of osseointegration is tied to the porosity of the bone and the ability of the implant to exchange active ion sites with the bone. Titanium and its alloys are the materials of choice clinically, because of their excellent biocompatibility and superior mechanical properties as indicated in [17]. The combined effect of surface energy, surface roughness, and topography on the implant determines its ultimate ability to integrate into the surrounding tissue. Surface modification technologies involve preparation with either an additive coating or a subtractive method. Cell migration, adhesion, and proliferation on implant surfaces are important prerequisites to initiate the process of tissue regeneration, while modifications of the implant surface by incorporation of biologic mediators of growth and differentiation may be potentially beneficial in enhancing wound healing following implant placement.

### *M. Contact problems with friction, adhesion, and wear in orthopaedic biomechanics. I: General developments*

The bone-implant interface behavior is far from being fully recognized and understood; also, one lacks reliable phenomenological models as it was mentioned in [18]. Along with mentioning the various problems with joint and bone implants, this article mentions the lack of models that can predict the behavior of implants.

### *N. Spine Interbody Implants: Material Selection and Modification, Functionalization and Bioactivation of Surfaces to Improve Osseointegration*

Achieving bone integration with an interbody implant is likely to aid fusion and improve implant longevity by limiting subsidence and stress shielding and associated complications. Surface modification and/or conversion of implant surfaces into bioactive areas is intended to improve in-growth and on-growth were discussed in [19]. Along with mentioning the various problems with joint and bone implants, this article underlines the lack of models that can predict the behavior of implants.

### *O. Dynamic bone quality-a non-invasive measure of bone's biomechanical property*

Using dual x-ray absorptiometry (DXA), bone mineral density (BMD) is usually measured to detect osteoporosis. Combing this test with a damping factor test is indicative of fractures in one of several places as shown in [20]. This is useful because it indicates a factor that can be accounted for, and modeled for, reducing prosthetic failure by upping the damping factor of the material. The idea that complementing the prosthetic in other places of the body is also interesting and makes sense given that having a stronger material in one place might create a different failure point.

### *P. Bone biology, osseointegration, and bone grafting*

The structural integrity of bone may be compromised in times of normal metabolic calcium need and in disease states, thus altering bone structure and mass. This phenomenon can be noted in the bone structure of postmenopausal women, who experience a decrease in estrogen hormones. As bone mass is lost, the interconnections between bone trabeculae also are lost. Because normal interconnections play an important role in making bone a biomechanically rigid structure, this decrease leads to fragility and failure of the bone structure presented in [21]. It is important to note that gender plays a role in the structure, since the absorption rate of calcium is different between men and women, and it is suggested that it is even different between races/ethnicities. Quantifying these differences is important for the model to work.

### *Q. Methods for assessing bone quality*

Methods for characterizing bone geometry and microarchitecture include quantitative CT, high-resolution peripheral quantitative CT, high-resolution MRI, and micro-CT. Outcomes include three-dimensional whole-bone geometry, trabecular morphology, and tissue mineral density. The primary advantage is the ability to image non-invasively; disadvantages include the lack of a direct measure of bone strength. Methods for measuring tissue composition include scanning electron microscopy, vibrational spectroscopy, nuclear magnetic resonance imaging, and chemical and physical analytical techniques. Outcomes include mineral density and crystallinity, elemental composition, and collagen crosslink composition. Advantages include the detailed material characterization; disadvantages include the need for a biopsy as discussed in [22].

The article concludes that although no single method can completely characterize bone quality, current noninvasive imaging techniques can be combined with ex-vivo mechanical and compositional techniques to provide a comprehensive understanding of bone quality.

### *R. Biomechanical background for a noninvasive assessment of bone strength and muscle-bone interactions*

Bones would not control their mass in order to optimize their strength. They would rather control their architecture to optimize their structural stiffness. No solid structure fails without undergoing some tensile strain at some point. Therefore, the chief skeletal property concerning body-weight bearing is stiffness (i.e., the relationship between the load on a bone and its deformation). A rigid material (mineralized collagen) seems to have developed during evolution for building bones. However, the mechanical efficiency of bones seemed not to depend on the mere accumulation of material but rather on the optimization of its spatial distribution demonstrated in [23]. This contrasts with other articles mentioned here, which list the rate of absorption for minerals as a linear property without regard to its spatial distribution.

### *S. Biomechanical consideration in osseointegrated support protheses*

Biomechanics are of two types: Reactive and Therapeutic. Reactive biomechanics refers to the interaction of isolated biomechanical factors which when combined, produce an accumulative effect and therapeutic refers to the clinical process of altering each biomechanical factor to reduce the cumulative response causing implant overload and failure as revealed in [24]. Biomechanical failures do occur due to deficient knowledge of the forces the implant would be subjected to. Hence it is always necessary for the team professionals to have a thorough knowledge of the basic principles of biomechanics and plan the treatment accordingly.
This reinforces the need to pre-plan and therapeutically alter the biomechanics to help osseointegration.

### *T. Muscle Strength and Bone Mineral Density in mine victims with transtibial amputation*

Local muscle strength and muscle contractions are important factors for local bone mineral density and these factors need to be paid more attention to in amputee patients. Bone mineral density and muscle strength are lower on the amputated side than on the sound side and local bone loss is related to the loss of muscle strength in transtibial amputees shown in [25]. This article is important because it highlights the need to account for the muscle density of the patient.

### *U. Revolutionizing Prosthetics: Extreme Trans-disciplinary Systems Engineering*

An overview of a Defense Advanced Research Projects Agency (DARPA) project that created an advanced upper-limb prosthetics. They importantly concluded that when it comes to choosing to implement such a procedure on a person, that one size (or in this case prosthetic) does not fit all and that it must be tailored to use, biology, cost, and expectations. Each approach had risks and rewards, and ultimately the choice should be made by the patient and his/her clinician. As a result, a multimodal neural integration framework should be designed to use one or more approaches in synergy with each other as discussed in [26].

### *V. Noninvasive imaging of bone microarchitecture*

High-resolution peripheral quantitative computed tomography (HR-pQCT) imaging requires a dedicated extremity scanner. Using HR-pQCT, measures of three-dimensional (3D) bone geometry, overall and compartment-specific bone density, and bone microarchitecture can be acquired within a scan time of 3 minutes. Cross-sectional HR-pQCT studies have also provided insight into the age, race, and gender-specific aspects of bone quality. Asian men and women have smaller bones; thus BMD, as measured by DXA, tends to underestimate their real bone density. Nevertheless, Asians sustain fewer fractures. Using HR-pQCT, it was found that despite the relatively low total bone area, premenopausal Asian women displayed significantly thicker cortices and a richer trabecular microarchitecture than Caucasians. The finite elements (FE) analyses yielded higher estimates of bone stiffness/strength. Menopause diminishes some of these microstructural advantages, but significant racial differences remain detectable according to [27].

This study solidifies HR-pQCT as a good candidate for use in procedure since it yields the most information from one test, and it furthers the idea introduced by [21] that race plays a role in bone density.

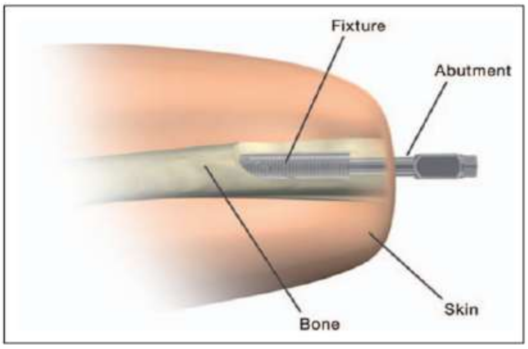
### *W. Noninvasive evaluation of bone micro-architecture and strength*

Noninvasive imaging techniques, including quantitative computed tomography (QCT), high-resolution peripheral QCT (HR-pQCT), and magnetic resonance imaging (MRI) allow for the assessment of bone microarchitecture and strength, which are thought to underlie fracture risk. The researcher concentrated on the potential clinical utility of these techniques to enhance understanding of the skeletal changes that occur during growth and aging, differences between male and female skeletons, the assessment of the response to drug therapies, and the identification of patients at risk of fracture. At least in those first three areas, the new imaging systems appear poised to serve as invaluable research tools that ultimately may offer an understanding of fracture mechanisms far beyond what DXA can provide. However, they are unlikely to supplant DXA any time soon in the realm of fracture risk prediction.

This is because 'While more work is needed looking at other sites, like the spine, in general, these biomechanical findings fit with the growing epidemiological data suggesting that DXA works regardless of gender, in part because it's so influenced by bone size as shown in [28]. There is also the consideration that these other imaging tools are much more specialized and finicky to research with, as the same machine must be used through the whole process and the setup must be the same every time, a detail that according to the author's opinion is enough to discard them entirely.

### *X. Osseointegration amputation prostheses on the upper limbs: methods, prosthetics, and rehabilitation*

Traditional prosthetic socket and suspension technology often fail to meet both cosmetic and functional requirements, which can severely impair quality of life. With direct bone anchorage, the prosthesis is attached to the residual limb without the use of a socket. The method is based on the principle of osseointegration, which has been in clinical use for tooth and maxillofacial replacements since 1965 as described by [3].



*F*ig. 1. Implant System-The implant system incorporates three main components: a threaded titanium implant (the fixture), a skin-penetrating cylindrical implant (the abutment), and a titanium screw (the abutment screw) which holds the system together [29].

*This article gives a good overview of osseointegration and gives suggestive data about possible problems with implementation, but the big takeaway here is that careful consideration of implementation yields the best results.*

### *Y. Skeletal Scintigraphy (Bone Scan)*

*Measures bone elasticity, the structure of trabecular, and apparent density. The common site of measurement is the non-dominant calcaneus, which a laterally projecting piezoelectric transducer transmits US energy toward a receiving transducer. The material determines the velocity and degree of penetration of the sound waves. Greater penetration (less attenuation) and lower velocity are possible with more porous bone (slower wave). The calcaneus has several advantages as a QUS measurement site: it can be viewed via two almost plane-parallel surfaces; it is primarily made up of trabecular bone, which is more metabolically active than cortical bone; the soft tissue above it is thin, and it is a weight-bearing bone. The broadband ultrasonic attenuation (BUA, m/s), ultrasound velocity (speed of sound—SOS, dB/MHz), and a computed stiffness index based on the product of BUA and SOS modified by three distinct constants are commonly used to measure composite bone qualities as indicated in [30]. QUS devices are small, portable, and relatively inexpensive and operator training. Can be performed quickly and without exposure to ionizing radiation.*

### *Z. Resonant Ultrasound Spectroscopy: theory and application*

*In various musculoskeletal diseases and diagnostic orthopedic medicine, bone scintigraphy is one of the most utilized diagnostic procedures to study bone lesions and metastases. Later advancements, such as single-photon emission computed tomography (SPECT) and positron emission tomography (PET), have made it possible to acquire whole-body scans of the whole skeleton. They improve lesion detection sensitivity and, more critically, allow for 3D localization of radiation generated by radionuclide imaging agents or biomarkers, with detection sensitivity down to nano- or picomolar concentrations. The expansion of clinical nuclear imaging applications has resulted in the creation of a dedicated small animal imaging system presented in [31]. In osteoarthritis, alterations in bone turnover and cartilage composition can be detected. Micro-SPECT/micro-CT co-imaging can detect high uptake of Tc-99 m MDP, imaging areas with high bone turnover, such as joints (knees, shoulders), spine, and skull.*

### *AA. Resonant Ultrasound Spectroscopy*

Resonant Ultrasound Spectroscopy (RUS) is an elegant strategy for measuring the total elastic tensor of a fabric. The scheme utilizes the reality that the mechanical vibration resonance range depends on the geometry, mass density, and elastic tensor of the test. RUS to utilize these conditions to gather flexible properties or shape parameters of tests from a suite of measured resonance frequencies as demonstrated by [32]. To perform a reversal, we must have a way of anticipating these frequencies for an arbitrary elastic body. Normal modes of elastic substances are used in Resonant Ultrasound Spectroscopy (RUS) to determine material properties such as elastic moduli. In theory, a single measurement could be used to infer the entire elastic tensor. RUS bridges the experimental gap between low-frequency stress-strain methods (quasi-static up to a few kHz) and ultrasonic time-delay methods for centimeter-sized samples (hundreds of kHz to GHz).

### *BB. Imaging-Based Methods for Non-invasive Assessment of Bone Properties Influenced by Mechanical Loading*

Skeletal scintigraphy makes a difference to diagnose and evaluate an assortment of bone diseases and conditions utilizing little sums of radioactive materials called radiotracers that are infused into the circulation system. The radiotracer voyages through the zone being inspected and gives off radiation within the shape of gamma beams which are identified by an uncommon gamma camera and a computer to form pictures of your bones as mentioned in [33]. Since it can pinpoint atomic movement inside the body, skeletal scintigraphy offers the potential to recognize illness in its most punctual stages. The common uses of the bone scan are to help determine the location of an abnormal bone in complex bone structures, such as the foot or spine. diagnose broken bones, such as a stress fracture or a hip fracture, not clearly seen on x-rays, and find bone damage caused by infection or other conditions.

### *CC. Imaging Technologies for Preclinical Models of Bone and Joint Disorders*

Investigative devices are being created to build computer-based 3D geometric models of bone inferred from serial transaxial whole-body QCT, HR-pQCT, and HR-MRI imaging utilizing FEA. Whole-body QCT pictures are post-processed utilizing a commercially accessible program to create 1 to 3 mm bone voxels, which are changed over into similarly measured "finite elements"—each relegated homogeneous fabric flexible properties agent of human cortical or trabecular bone as explained in [34]. Additionally, μFEA models can be built from HR-pQCT and HR-MRI filters of peripheral skeletal sites at an indeed higher ostensible determination to supplying a point-by-point representation of the microstructure.

"Virtual" loads (i.e., to recreate powers related with compression, bowing, single-leg position, or sideways drop) are connected to a volumetric locale intrigued to foresee fabric properties such as flexible modulus, stresses, disappointment stack, and rate of stack carried by distinctive bone locales.

## III. METHODOLOGY

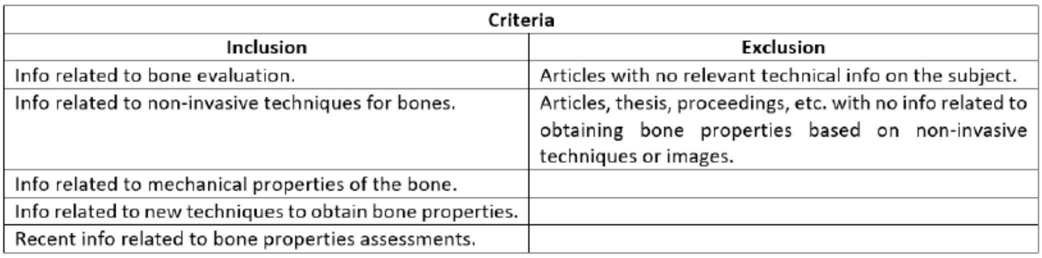
During this review, which is related to obtaining mechanical properties from non-invasive techniques, the focus of this literature review was carried out taking into consideration scientific articles and theses, publications in physical and digital format and presentations at conferences provided by authors, librarians, and scientific entities.

In addition, American and European databases were searched, including the repositories of academic institutions specialized in the field of biomedical engineering. Finally, a little information was obtained from sources such as engineering textbooks, technical manuals, medicine and engineering handbooks, the internet, and review articles.

Originally, an exhaustive search was carried out in the main database of the Polytechnic University of Puerto Rico, obtaining fifty-five (55) articles related to the topic above, filtering the publication periods from ranges between 2000 to 2022. Among the most common search and databases used for this review are "PubMed", "Scopus", "IEEE", "EBSCO", "Google Scholar" and "Science Direct", among others.

However, only thirty-five (35) articles were selected since they showed a strong correlation with the main purpose of the review. The twenty (20) rejected articles were evaluated to determine which of these would meet the inclusion or exclusion criteria. For each criterion, several elements were created that helped either to accept or reject the articles to be included in this review, including the technical knowledge and characteristics of the intended topic (See table 1 below).

Table 1. Inclusion and Exclusion Criteria



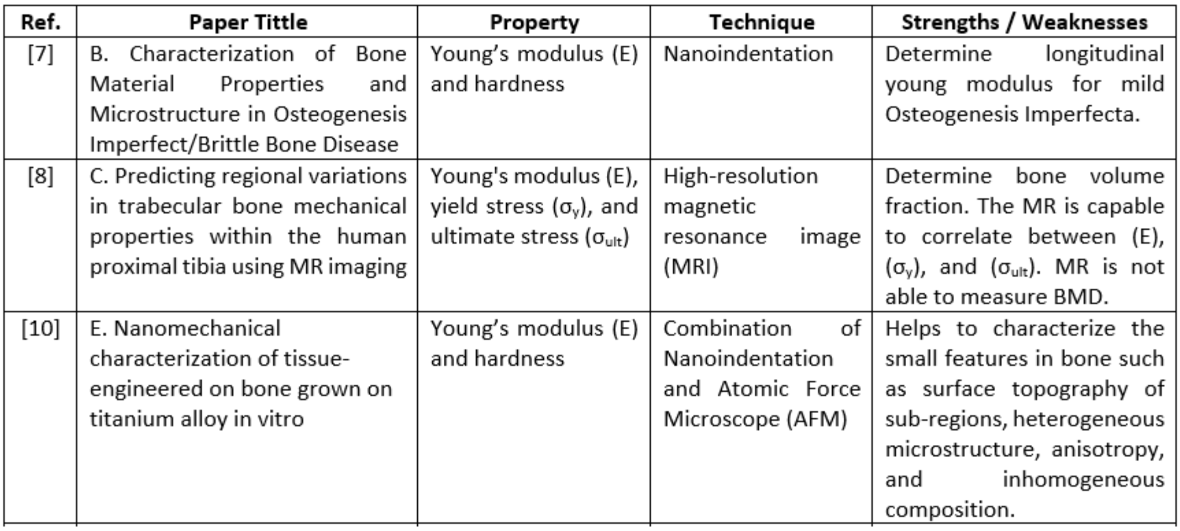
| **Criteria** | |
|---|---|
| **Inclusion** | **Exclusion** |
| Info related to bone evaluation. | Articles with no relevant technical info on the subject. |
| Info related to non-invasive techniques for bones. | Articles, thesis, proceedings, etc. with no info related to obtaining bone properties based on non-invasive techniques or images. |
| Info related to mechanical properties of the bone. | |
| Info related to new techniques to obtain bone properties. | |
| Recent info related to bone properties assessments. | |

The keywords used within the revision of this article were as follows:

·"Mechanical Properties" and "Non-Invasive Techniques"
·"Stress-Strain Relationship" and "Non-Destructive Techniques"
·"Bone Characterization" and "Bone Diagnosis"
·"Young Modulus" and "Cortical Bone"
·"Mechanical properties correlation" and "Images"
·"Bone Mineral Content (BMC) Evaluation" and "Bone Mineral Density (BMD) Evaluation"

## IV. RESULTS

Table 2. Most Relevant Papers to Obtain Mechanical Properties Based on Non-Invasive Techniques.



| **Ref.** | **Paper Tittle** | **Property** | **Technique** | **Strengths / Weaknesses** |
|---|---|---|---|---|
| [7] | B. Characterization of Bone Material Properties and Microstructure in Osteogenesis Imperfect/Brittle Bone Disease | Young's modulus (E) and hardness | Nanoindentation | Determine longitudinal young modulus for mild Osteogenesis Imperfecta. |
| [8] | C. Predicting regional variations in trabecular bone mechanical properties within the human proximal tibia using MR imaging | Young's modulus (E), yield stress ($\sigma_y$), and ultimate stress ($\sigma_{ult}$) | High-resolution magnetic resonance image (MRI) | Determine bone volume fraction. The MR is capable to correlate between (E), ($\sigma_y$), and ($\sigma_{ult}$). MR is not able to measure BMD. |
| [10] | E. Nanomechanical characterization of tissue-engineered on bone grown on titanium alloy in vitro | Young's modulus (E) and hardness | Combination of Nanoindentation and Atomic Force Microscope (AFM) | Helps to characterize the small features in bone such as surface topography of sub-regions, heterogeneous microstructure, anisotropy, and inhomogeneous composition. |

| | | | | |
|---|---|---|---|---|
| [15] | J. Noninvasive Measurements of Bone Mass, Structure, and Strength: Current Methods and Experimental Techniques | Bone mineral content and bone mineral density | Dual-photon absorptiometry single-photon absorptiometry, dual energy X-ray absorptiometry, and quantitative computed tomography | Distinguish between patients with and without osteoporosis. |
| [16] | K. Measurement of abnormal bone composition in vivo using noninvasive Raman spectroscopy | Porosity | Spatially Offset Raman Spectroscopy | Retrieve info noninvasively from both the mineral and proteins of the bone. |
| [20] | O. Dynamic bone quality-a non-invasive measure of bone's biomechanical property | Bone mineral density (BMD) | Using dual x-ray absorptiometry (DXA) | Used to measure and detect osteoporosis. |
| [22] | Q. Methods for assessing bone quality | Microstructure and Microarchitecture | Quantitative CT, high-resolution peripheral quantitative CT, high-resolution MRI, and micro-CT. | Provide bone geometry and microarchitecture. Includes 3D bone geometry, trabecular morphology, and tissue mineral density. |
| [27] | V. Noninvasive imaging of bone microarchitecture | Bone Mineral Density and microarchitecture | High-resolution peripheral quantitative computed tomography (HR-pQCT) | Obtain 3D bone geometry, overall and compartment-specific bone mineral density, and bone microarchitecture. |
| [28] | W. Noninvasive evaluation of bone micro-architecture and strength | Microarchitecture, strength, fracture, and bone mineral density (BMD) | Quantitative computed tomography (QCT), high-resolution peripheral QCT (HR-pQCT), magnetic resonance imaging (MRI) and Dual-energy X-ray absorptiometry (DXA) | The QCT, HRpQCT and MRI allow for the assessment of bone microarchitecture and strength. DXA help to predict bone fracture. |
| [30] | Y. Skeletal Scintigraphy (Bone Scan) | Young's Modulus, microarchitecture of trabecular bone, and apparent density. | Skeletal Scintigraphy | Bone scintigraphy is one of the most utilized diagnostic procedures to study bone lesions and metastases. |
| [31] | AA. Resonant Ultrasound Spectroscopy | Young's Modulus | Resonant Ultrasound Spectroscopy (RUS) | The scheme utilizes the reality that the mechanical vibration resonance range depends on the geometry, mass density, and elastic tensor of the test. |

## CONCLUSIONS

It has been noticed that exists a gap of knowledge regarding the non-invasive evaluation of bones to determine their mechanical properties. There is a lack of non-invasive standards and their associated availability in the market, which makes difficult the evaluation concerns prosthetic and medical device fitting. Also, it can be concluded that non-invasive techniques are extremely useful when evaluations of bone diseases are needed. The bone diseases such as osteogenesis imperfecta, osteoporosis, and micro-fractures can be predicted in advance with these types of non-invasive techniques. Based on the above review, one of the most promising non-invasive techniques is the one related to the evaluation of the porosity of bone, which shows a significant connection with medical practices and their current challenges. Even this practice is in dispute, for example, [23] suggests that the rate of absorption and accumulation of minerals is not a linear relationship but that it does accumulate in a pattern that suggests that the body accumulates favoring stiffness rather than strength or flexibility. This is in contrast with most other relevant articles listed here that state that accumulation leads to hardness and absent that, osteopenia occurs (low bone mineral density).

There is also the notion that different regions of the body contain different kinds of bone and was observed that each of these bones has a different hardness and modulus. Besides that, it was noticed that the cancellous bone in the tibia was approximately half as hard as the thigh bone according to [35].

A mathematical or engineered model does not yet exist that joins this knowledge with a mechanic evaluation of materials. In addition, aggregating this validated knowledge to new emerging biomaterials would better address current shortfalls of osseointegration, bone remodeling, and their associated mechanical characteristics and properties and would synergistically improve our insights into prosthetic/orthopedics applications.

## ACKNOWLEDGMENT

I want to thank the library and public services personnel of the Polytechnic University of Puerto Rico to support me in finding some of the articles through an interlibrary loan agreement with other libraries around the world. Also, the UNEXPO, Puerto Ordaz for their constant support and guidance throughout these years.

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