Analysis of bone mineral density of human bones for strength evaluation

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MS received 27 November 2013; revised 29 December 2014;

accepted 27 February 2015

Abstract. The bone density (BMD) is a medical term normally referring to the amount of mineral matter per square centimetre of bones. Twenty-five patients (18 female and 7 male patients with a mean age of 71.3 years) undergoing both lumbar spine DXA scans and computed tomography imaging were evaluated to determine if HU correlates with BMD and T-scores. BMD is used in clinical medicine as an indirect indicator of osteoporosis and fracture risk. This medical bone density is not the true physical “density” of the bone, which would be computed as mass per volume. Dual-energy X-ray absorptiometry (DXA, previously DEXA), a means of measuring BMD, is the most widely used and most thoroughly studied bone density measurement technologies. Different types of bone strength are required for various applications, but this strength calculation requires different machines for each strength property or it is done by different software like X-ray, CT scan, DEXA and BIA. The paper includes the design of an experimental setup which performs different types of test like tension, compression, three point bending, four point bending and torsion. The modified correlation between BMD and HU for various strength calculations is found out and validated with the experimental results.

Keywords. Bone mineral density; BIA; DEXA; strength; testing.

1. Introduction

The femur or thigh bone is the most proximal (closest to the body) bone of the leg in vertebrates capable of walking or jumping. In human anatomy, the femur is the longest and largest bone. The average adult male femur is 48 cm (18.9 in) in length and 2.34 cm (0.92 in) in diameter and can

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support up to 2 times the weight of an adult. It forms part of the hip joint (at the acetabulum) and part of the knee joint, which is located above. There are four eminences, or protuberances, in the human femur: the head, the greater trochanter, the lesser trochanter, and the lower extremity. They appear at various times from just before birth to about age 14 (Cristofolini *et al* 2006).

BMD is defined as means value expressed in Hounsfield units of each pixel. Bone material presents a complex behaviour involving heterogeneous and anisotropic mechanical properties. Moreover, bone is a living tissue; therefore, its microstructure and mechanical properties evolve with time in a process called remodelling. This phenomenon has been studied from a long time and there are many numerical models that have been formulated in the sense to predict the density distribution in various bones, mainly in the femur. A femur, tibia and mandible (all human) were scanned and the image stored in a DICOM format. DICOM images are imported in MIMICS software and different properties like BMD with Hounsfield units (HU) for 50 different materials were assigned to relate the bone mass density (Cristofolini *et al* 2006; Cesar Libanati *et al* 2009). Correlations between BMD, HU and mechanical strength properties were studied and correlation is formulated for the same (Rho *et al* 1995).

1.1 Aims and objectives

The correlation between BMD, HU and various mechanical strength properties is evaluated for cortical and cancellous bones from various body locations in various directions. The good correlations were found to exist for cancellous bone and poor for cortical bone. The aim of the present study includes

- To evaluate more accurate correlation for cortical and cancellous bones of femur.
- To statically analyse various methods to find BMD and related material properties.
- To develop online methodology to estimate BMD and related material properties.
- To find more accurate correlation for BMD, BMC, HU, E, ρ
- To design experimental setup to find out various mechanical properties on single machine.

1.2 Biomechanics of bone

Strength and stiffness are typically used to define the “health” of a bone. The slope of the curve is called as Young’s modulus (E), whereas height of the curve represents the ultimate strength. The yield point represents a transition, above which strains begin to cause permanent damage to the bone structure. Post-yield strain is inversely proportional to the brittleness of the bone (Hanumantharaju & Shivanand 2010).

Graph 1. Stress–Strain Diagram for bone.

Bone mineral density (BMD) is highly correlated with strength and stiffness, but there is an inverse relationship between bone stiffness (Young's modulus) and ultimate strain, shown in graph 1.

Bone samples are prepared from cortical and cancellous bones from proximal femur body parts. Three cadaver bone samples are prepared (two cancellous and one cortical bone) derived from proximal femur. These were tested on three-point hydraulic experimental setup. The observation tables for the same are as follows.

Table 1. The values of elongation, ultimate load, breaking load for various specimens.

Sr. no	Specimen	Elongation (mm)	Ultimate load (kN)	Breaking load (kN)	Elongation (mm)	Strain	UTS (N/mm ²)
1	Sample-1	27.03	68.1	43.89	27.03	0.54	867.18
2	Sample-2	29.38	68.35	42.69	29.38	0.58	870.25
3	Sample-3	21.94	68.14	42.84	21.94	0.43	867.58

The overall dimensions of the proximal femur are as follows:

Sample 1:

1. Gender: Male
2. Age: 45 years
3. Diameter: 44 mm
4. Average diameter: 28 mm
5. Width: 75 mm
6. Total length: 450 mm

Sample 2:

1. Gender: male
2. Age: 47 years
3. Diameter: 44 mm
4. Average diameter: 29.36 mm
5. Width: 77.5 mm
6. Total length: 470 mm

Sample 3:

1. Gender: Male
2. Age: 46 years
3. Diameter: 44.5 mm
4. Average diameter: 28.5 mm
5. Width: 76 mm
6. Total length: 460 mm

1.3 Hydraulic experimental setup

Figure 1. Hydraulic experimental setup.

1.4 Design of hydraulic experimental setup

Different types of bone strength are required for various applications like predicting bone fracture but these strength calculations requires different machines for each strength property or it is calculated by putting scanned data from X-ray, CT scan, DEXA, BIA etc. in existing correlations. A hydraulic experimental setup is designed and fabricated to perform different types of test like tension, compression, 3-point bending, 2-point bending and torsion. This setup is easy to operate and easy to handle maximum forces. Main advantage of this setup is its low cost and its ability to perform different tests on single setup. This experimental setup is useful in cadaveric bone study for research purpose.

This setup works on the principle of hydraulic circuit. Working of this setup is very easy, as it consist of reservoir, gear pump, double acting cylinder, pressure relief valve, direction control valve, suction strainer, check valve, oil lever indicator, pressure gauge etc. Reservoir is provided for storage of fuel. When motor starts, Gear pump sucks the fuel from reservoir and passes to direction control valve (5/3 manually operated spring return DCV) through suction strainer and check valve. DCV has a maximum pressure of 210 bars.

DCV is operated manually by changing the lever. When DCV is in position 01, the oil is passed to double acting cylinder to the upward port and piston which is connected to the holder moves down during the forward stroke. The component or bone which is to be tested is placed on the bottom fixture and fixture is mounted on base plate. The load is applied on the bone.

Figure 2. Stress-Strain diagram for bone. Flowchart of program BIA.

Figure 3. Actual implemented circuit of BIA.

When DCV is in position 03, the oil from DCV is passed to bottom port of the double acting cylinder and piston moves up during the return stroke. Pressure gauge is provided to take up reading when bone or components breaks. From the pressure gauge readings we can find out the force applied to it. When DCV is in position 02, we can keep the position in hold-on position (Yuehuei & Robert 2000).

Z-score

Z-score is the number of standard deviations away from the average value of the reference group. A person who is average has a Z-score of 0 and is at the 50th percentile. If the Z-score is -0.84 then 20% of people has a lower bone density.

Calculation of Z score-

$$\text{Z-score} = (\text{patient's BMD} - \text{expected BMD})/\text{SD}$$

To calculate BMD if you know the Z-score, use the same equation by just rearranging it as

$$\text{BMD} = \text{Expected BMD} + (\text{Z-score} * \text{SD})$$

Table 2. Data table of BMD, T-score, Z-Score and BMC.

N	BMD	Z-Score	T-Score	BMC (BIA)	BMC (DEXA)
1	1.011	-0.8	-1.4	2.35	2.042
2	1.214	1.3	1.1	2.28	1.956
3	1.052	-1.6	2.1	2.64	2.237
4	1.116	0.1	0.1	2.1	2.19
5	0.922	-0.8	-2.5	2	1.703
6	1.125	-0.4	1.2	2.85	2.492
7	0.939	-1.2	-2.3	2.27	1.862
8	0.968	-1.6	-2	2.22	1.959
9	1.193	0.6	0.9	2.41	2.69
10	0.9373	-1.9	-1.9	2.5	2.13
11	1.015	-0.3	-0.9	2.24	2.017
12	1.019	-0.8	-1.3	2.05	2.016
13	0.943	-0.1	-2.3	1.82	1.326
14	1.018	-0.1	-1.3	1.85	1.823
15	1.044	-0.3	-1	2.02	1.958
16	1.22	-0.1	1.2	2.66	2.72
17	1.186	1	0.8	2.29	2.317
18	1.114	1.6	-0.1	1.9	2.01
19	1.279	0.6	0.7	1.76	2.953
20	1.199	0.7	0.9	1.86	2.478
21	0.876	-1.5	-3.1	1.93	1.416
22	1.109	0.5	-0.2	2.09	2.196
23	1.091	0.8	-0.4	2.13	2.048
24	1.161	2.1	0.4	1.86	1.882
25	1.112	0.6	-0.2	2.22	2.226

T-score

On the T-score scale, 0 represents normal, healthy bone density of a 30-year-old person (the age of peak bone density). T-scores above 0 and slightly below 0 are within the normal range. It works like a temperature scale & is shown in graph 2. A temperature of -2 is lower than a temperature of -1 . In the same way, a T-score of -2.3 shows lower bone density than a score of -1.8 (tables 1, 2, 3, 4 and 5) is shown in graphs 3 and 4.

Graph 2. T- Score and Z- Score versus BMC (DEXA) and BMC (BIA).

Graph 3. BMD versus Hounsfield unit.

A T-score of -1 to 0 and above is considered normal bone density, while a T-score between -1 and -2.5 is diagnosed as osteopenia. A score of -2.5 or below is diagnosed as osteoporosis. The T-score is a radiographic diagnosis, meaning it is an X-ray diagnosis and does not imply anything about the cause of osteoporosis (Raymond *et al* 2008).

Techniques of measuring BMD and HU:

1. DXA (formerly known as DEXA)

Dual-energy X-ray absorptiometry (DXA, previously DEXA) is a means of measuring bone mineral density (BMD). Dual Energy X ray absorptiometry uses two phantom rods in which X-ray attenuation of two phantom rods measures two different energy levels is shown in graphs 5, 6 and 7.

Graph 4. Pie chart analysis.

Graph 5. BMD versus age for male patients.

2. Bio-electrical impedance analysis (BIA)

It is one of the widely used methods for estimating the body composition. BIA measurement is quick, simple and non-invasive. It is familiar in the consumer market as a simple instrument for estimating body fat. Due to its benefits and features, it is used for calculating muscle mass, fat, water, tissue and bone mineral count of a person.

Table 3. Table Error comparison for correlation between BMD and HU for different methods.

	DEXA	CT SCAN	BIA
R2	0.735248	0.801851	0.824685
Standard Error of Estimate	0.785784	0.588107	0.520334

Table 4. Various age group data.

Sr.no.	Age group	Age	Gender	Weight	BMC	T-Score	Z-Score	BMD
1	Young	23	F	48.5	2.196	-0.2	0.5	1.109
2		24	F	53	2.016	-1.3	-0.8	1.019
3		34	F	95	2.72	1.2	-0.1	1.22
4		38	F	70	2.69	0.9	0.6	1.193
5		43	F	49	1.958	-1	-0.3	1.044
6		45	F	50	1.872	-1.5	-0.8	1.005
7	Young	45	M	80	3.031	-0.6	-0.7	1.168
8		47	F	62	2.317	0.8	1	1.186
9	Adult	48	F	65	2.19	-0.1	0.1	1.116
10		49	M	80	2.953	0.7	0.6	1.279
11	Adult	49	F	56	2.042	-1.4	-0.8	1.011
12		52	F	65	1.862	-2.3	-1.2	0.939
13		54	M	61	2.492	-1.2	-0.4	1.125
14		54	F	51	1.823	-1.3	-0.1	1.018
15		55	F	62	2.226	-0.2	0.6	1.112
16		55.6	F	55	2.01	-0.1	1.6	1.114
17		58	F	85	2.13	-1.9	-1.9	0.9373
18		58	M	88	2.478	0.9	0.7	1.199
19		58	F	65	2.095	-0.4	0.4	1.093
20		59	F	80	1.956	1.1	1.3	1.214
21		59	F	76	1.959	-2	-1.6	0.968
22		59	F	48	1.416	-3.1	-1.5	0.876
23		60	F	58	2.048	-0.4	0.8	1.091
24		63	F	43	1.326	-2.3	-0.1	0.943
25	Age	64	M	73.1	2.237	-2.1	-1.6	1.052
26		64	F	74	2.017	-0.9	-0.3	1.015
27		66	F	56	1.882	0.4	2.1	1.161
28	Match	66	F	55	1.703	-2.5	-0.8	0.922
29		68	F	88	2.11	-0.6	-0.3	1.086
30		70	F	65	1.503	-3.4	-2	0.857
31		72	M	72	2.584	-0.7	0.1	1.163

Table 5. Correlation between BMD and HU.

n	BMD(Y)	H.U.(X)	X ²	X ³	X ⁴	X*Y	X ² *Y
1	1.011	580.7	337212.5	195819293	1.14E+11	587.0877	340921.8
2	1.214	591.23	349552.9	206666169	1.22E+11	717.7532	424357.2
3	1.052	598.54	358250.1	214427034	1.28E+11	629.6641	376879.1
4	1.116	603.28	363946.8	219561800	1.32E+11	673.2605	406164.6
5	0.922	607.35	368874	224035638	1.36E+11	559.9767	340101.8
6	1.125	619.72	384052.9	238005250	1.47E+11	697.185	432059.5
7	0.939	632.81	400448.5	253407813	1.60E+11	594.2086	376021.1
8	0.968	640.63	410406.8	262918906	1.68E+11	620.1298	397273.8
9	1.193	644.89	415883.1	268198860	1.73E+11	769.3538	496148.6
10	0.9373	649.5	421850.3	273991737	1.78E+11	608.7764	395400.2
11	1.015	650.29	422877.1	274992739	1.79E+11	660.0444	429220.2
12	1.019	658.23	433266.7	285189162	1.88E+11	670.7364	441498.8
13	0.943	661.53	437621.9	289500043	1.92E+11	623.8228	412677.5
14	1.018	665.19	442477.7	294331765	1.96E+11	677.1634	450442.3
15	1.044	670.56	449650.7	301517783	2.02E+11	700.0646	469435.3
16	1.22	676.39	457503.4	309450746	2.09E+11	825.1958	558154.2
17	1.186	683.8	467582.4	319732872	2.19E+11	810.9868	554552.8
18	1.114	691.27	477854.2	330326282	2.28E+11	770.0748	532329.6
19	1.279	696.96	485753.2	338550579	2.36E+11	891.4118	621278.4
20	1.199	701.01	491415	344486843	2.41E+11	840.511	589206.6
21	0.876	713.97	509753.2	363948464	2.60E+11	625.4377	446543.8
22	1.109	719.25	517320.6	372082815	2.68E+11	797.6483	573708.5
23	1.091	727.93	529882.1	385717066	2.81E+11	794.1716	578101.4
24	1.161	731.57	535194.7	391532361	2.86E+11	849.3528	621361
25	1.112	739.85	547378	404977630	3.00E+11	822.7132	608684.4
26	1.163	743.5	552792.3	411001038	3.06E+11	864.6905	642897.4
27	1.086	748.28	559923	418979151	3.14E+11	812.6321	608076.3
28	0.587	761.92	580522.1	442311388	3.37E+11	447.247	340766.5
29	1.093	773.52	598333.2	462822689	3.58E+11	845.4574	653978.2
30	1.005	788.28	621385.4	489825650	3.86E+11	792.2214	624492.3
Total	31.7973	20371.95	13928965	9.59E+09	6.64E+12	21578.98	14742733

The technology actually determines the electrical impedance of body tissues, which provides an estimate of total body water (TBW). Using values of TBW derived from BIA, one can then estimate fat-free mass (FFM) and body fat mass (FM). In addition to its use in estimating FM, BIA is beginning to be used in the estimation of body cell mass (BCM), TBW and bone mineral count (BMC) in a variety of clinical conditions as shown in figures 1 and 2.

BIA measures the opposition of body tissues to the flow of a small (less than 1 mA) alternating current. Impedance is a function of two components (vectors): the resistance of the tissues themselves, and the additional opposition (reactance) due to the capacitance of membranes, tissue interfaces, and non-ionic tissues. The measured impedance is approximately equivalent to that of muscle tissue. Impedance is a function of frequency of the current used (typically 50 kHz, when a single frequency is used). Applications of BIA increasingly use multi-frequency measurements, or a frequency spectrum to evaluate differences in body composition caused by clinical and nutritional status. In actual use, however, BIA calculations of an individual's body fat may vary by as much as 10% of body weight because of differences in machines and methodologies used as shown in figure 3 (Patil *et al* 2012).

Graph 6. BMD versus age for female patients.

Graph 7. HU versus BMD for 25 patients.

2. Results and discussions

In general the methodology and approach for assessing the value of BMD and HU for various patients are studied and compared. The value of BMD is calculated and error analysis for various methods is carried out by using the various methods to assess the most accurate method. The value of T-score, Z-score, BMC, BMD is calculated by using CT scan data and material properties are evaluated by using Mimics software for various patients. This data helps in analysing the value of BMD accurately for various patients.

The different values of BMD, T-score, Z-score, BMC, HU are calculated by using regression analysis and JMP software. The BIA and DEXA are found to be more accurate compared CT

Table 6. The average value of various bone strengths are found as below.

	Cortical bone (N/mm ²)	Cancellous bone (N/mm ²)
Average tensile strength	178.65	4.4
Average compression strength	138.40	5.0
Modulus of rigidity	67.30	3.0

scan analysis. The designed experimental set up is used for finding the tensile and compression strengths for proximal femur (as shown in Table 6). Modified correlation between BMD and HU are validated with the help of experimental results. The analysis is carried out for various age groups (male and female). The exact correlations between BMD and HU for various patients are established. This will help in finding the value of BMD more accurately.

Modified Correlation for cancellous bone is:

$$\text{BMD} = \{(-1.39119) \cdot 106 \cdot (\text{HU})^2\} + \{2.59044 \cdot 103 \cdot (\text{HU})\} - 0.10278$$

Modified Correlation for cortical bone is:

$$\text{BMD} = \{(-2.1987) \cdot 10 - 6 \cdot (\text{HU})^2\} + \{2.8489 \cdot 10 - 3 \cdot (\text{HU})\} + 0.14613$$

3. Conclusions

The correlation between BMD and HU is calculated for cortical and cancellous bones and the correlation is validated with the experimental set up for finding the bone strength. In both the bone types, R² values are more than 90 % giving good correlation. For young adult (age group 43–49) the average value of BMD for male patients is 1.2235 while for female patients it is 1.0724. For adult (age group 52–60), the average value of BMD is 1.1624 while for female patients it is 0.9406. For age group (age match group 60–72), the average value of BMD is 1.1075 while for female patients it is 1.0158. BMD was measured by using BIA method and DEXA. BIA measurements were found more accurate. For males as well as females, as the age goes on increasing, the value of BMD goes on decreasing. Though for, both males and females, the value of BMD appears decreasing considerably after the age of 40, the rate of decrease is found more in case of women patients. Four point hydraulic experimental setup was developed for bone strength evaluation and validation of correlations between HU and BMD. For cancellous bone the percentage error was found between 0.20 to 0.5 and for cortical bones the percentage error was found between 0.3 to 0.32. Additional mechanical experiments are warranted to make comparisons between the structure-property relationships in bone.

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