

Measuring Structural Dynamic Properties of Human Tibia by Modal Testing

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Nomenclature

α_{jk} : receptance

${}_sA_{jk}$: s^{th} modal constant

ω_s : s^{th} natural frequency

ω : frequency

η_s : s^{th} loss factor

ABSTRACT

Identifying structural dynamic properties of human bones seems to be a promising technique in diagnosing metabolic bone diseases such as osteoporosis and in monitoring fracture healing. The major aim of this work is to observe the changes in the “loss factor” of human tibia with decreasing mineral density which is known as the main indicator of osteoporosis. In this preliminary stage of the study, the experiments are carried out in vitro, on tibia specimens obtained from fresh-frozen cadavers, as well as on dry tibia. The specimens that are placed on a soft rubber to have free-free boundary conditions are excited by an impact hammer and the response is measured using an accelerometer. The measured frequency response functions (FRFs) are analyzed using modal identification techniques to extract the modal parameters of the human tibia. It is observed that the regenerated FRFs from the modal model closely match with the experimentally measured ones, which is also an indication of the linear dynamic behavior of human tibia. Comparison of the modal parameters from fresh-frozen tibia with those obtained from dry tibia indicates that there is considerable change in the loss factor of tibia when it loses its mineral content and collagen. The results of a set of preliminary in vivo FRF measurements and the identified modal parameters are also presented in this study. It is concluded in this work that the modal loss factors identified from in vivo FRF measurements can be a good alternative in diagnosing progressing osteoporosis.

Keywords: biodynamic, tibia, modal identification of tibia, diagnosing osteoporosis

1. INTRODUCTION

Osteoporosis is a disease characterized by low bone mass and a micro-architectural deterioration of bone tissue, leading to enhanced bone fragility and a consequent increase in fracture risk (World Health Organization, 1994) with high socioeconomic impact on the society [1]. The common methods for detection of osteoporosis of the bone are dual energy X-ray absorptiometry (DXA) and quantitative computed tomography (QCT). According to World Health Organization T scores lower than -1.0 and -2.5 are called osteopenia and osteoporosis, respectively. Bone mineral density (BMD) measured by DXA and/or QCT is a predictor of mechanical bone

strength that has its limitations [2]. Fragility fractures in normal and osteopenic but sometimes not in osteoporotic patients are seen in medical practice. As a result, the need for better diagnosing of bone strength increases gradually [3].

Previous research [3-10] shows that osteoporosis could be diagnosed by vibration analysis, and as a result, this method is becoming an alternative diagnosis tool to identify the structure and strength of bones due to being noninvasive and precise. Earliest studies published by Perre et.al [7-10] mainly involve the assessment of natural frequencies and mode shapes of human bones (tibia and radius) both in vivo and in vitro using vibration and ultrasonic wave propagation analysis and finite element modeling. Results show that the natural frequencies of bones are decreasing with increasing level of osteoporosis, thus a correlation may exist and this can be used for the determination of bone strength.

Soft tissues and joints influence vibration measurements under in vivo conditions and interpretation of test results may be difficult. Perre et.al [8] investigated the effects of soft tissues on the structural dynamic characteristics of bones. Another attempt that has been done by Soethoudt et.al [11] reveals that the preload, that is applied by holding a small cylindrical metal element manually pressed at the excitation point while holding the accelerometer during the excitation of the bone via impact hammer, helps to decrease the damping effect of the skin and the underlying soft tissue. With vibration analysis of bone it is expected to have a better insight into the mechanical properties of bone in ex vivo and in vivo conditions.

The ultimate goal in this study is to obtain in vivo frequency response functions (FRFs) of human tibial bone and to develop a new approach to detect progressing osteoporosis by obtaining a correlation between structural dynamic properties and BMD measured by DXA and/or other properties of bone which causes osteoporosis. The most deficient part of the previous studies is that solely the change in natural frequency with progressing osteoporosis is investigated. However, natural frequencies of a structure depend on boundary conditions making it an inconvenient parameter for the assessment of osteoporosis, unless an experimental set up that prevents the change of boundary conditions of bone in each measurement is used. Therefore, it is believed that an alternative approach to detect progressing osteoporosis may be to investigate the change in "loss factor", which is an inherent property of bone.

In this preliminary stage of the study, the aim is first to determine the modal parameters of the tibia by ex vivo modal tests and then to carry out preliminary in vivo tests and thus to study the problems in monitoring the change in the loss factor of tibial bone from these measurements.

2. MODAL ANALYSIS OF TIBIA

2.1. Modal Parameters of Tibia

In order to obtain modal parameters of the tibia in vitro (ex vivo), a set of experiments are carried out on two specimens obtained through above knee amputations and show no history of diseases related to the tibia. The excitation is provided via an impact hammer (Dytran Instruments, type 5800B3, S/N 4354, sensitivity=48.5 mV/lbf) and the response was recorded using an accelerometer (Dytran Instruments, type 3035B, S/N=2436, sensitivity=104 mV/g). Both signals were measured simultaneously with an instrument of Data Physics, "QUATTRO", to obtain the FRF data.

The experiments are carried out with free-free boundary condition by placing tibia on a soft rubber as can be seen from Figure 1. Figure 2 shows the FRFs obtained for the two specimens and Figure 3 shows the coherence plots of the measurements which indicate that experimental data obtained are reliable.

The FRFs obtained were analyzed by using the modal identification software MODENT®. Circle and line fit methods are used for the identification of modal parameters. The natural frequencies, modal loss factors and modal constants of the modes identified for the two specimens are shown in Tables 1 and 2, respectively. The rigid body modes due to free boundary conditions and the flexibility of soft rubber are not identified and instead, mass and stiffness residuals are obtained as given in the tables. Although, the first modes are in the region of 300-400 Hz and the second ones are around 400-500 Hz, there are considerable differences between the natural frequencies of two specimens, as expected, since the two specimens are from two different cadavers and they do



Figure 1. Measurement of FRFs on fresh-frozen tibial bone

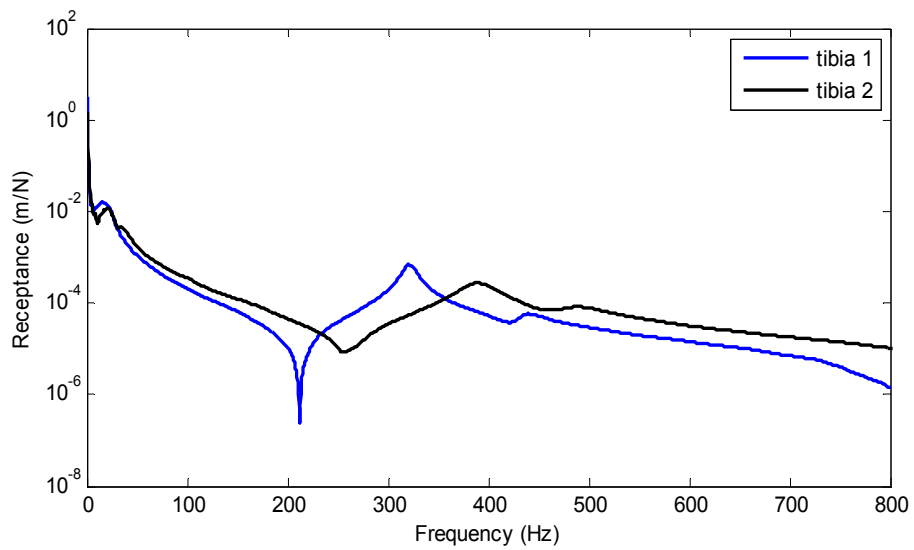


Figure 2. FRF plots of the two tibiae (fresh-frozen)

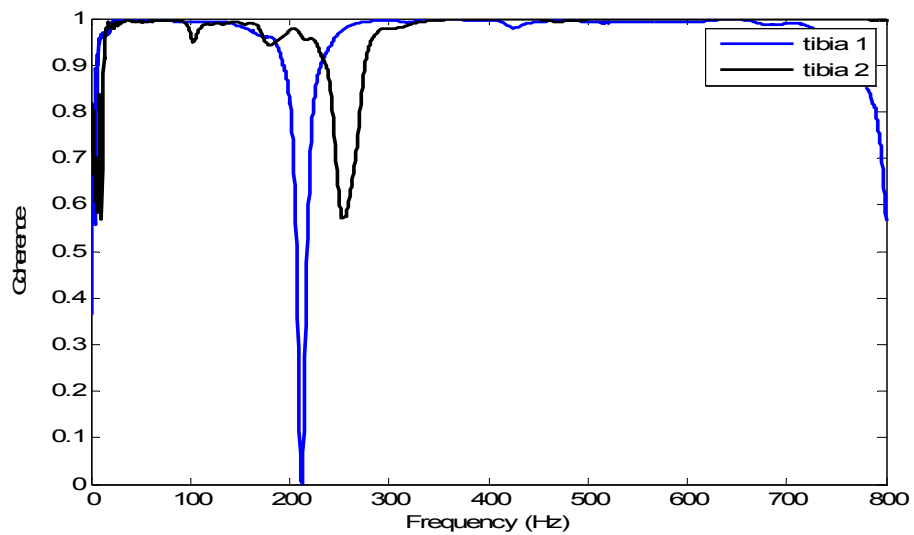


Figure 3. Coherence plots of the FRF measurements of the two tibiae (fresh-frozen)

not have identical geometries. However, the modal loss factors of the specimens were expected to be closer to each other. DXA tests showed that the mineral contents of both tibiae were not much different which implies that the differences between modal loss factors may only be partly due to the mineral content difference. Then it can be concluded that modal damping ratios of tibial bones are affected not only from the mineral content but also from the collagen which is the major organic component of the structure of bone. Yet, to be able to generalize this conclusion more specimens need to be tested.

Table 1. Modal properties of human fresh-frozen tibia (1)

Mode	Frequency (Hz)	Loss Factor	Modal Constant	Phase	Method
0	0.00	0.001	0.87932	21	Residual
1	321.27	0.040	1.3195	-2	0-Fit
2	438.34	0.054	0.11769	-44	L-Fit
3	1200	0.001	2.8932	-5	Residual

Table 2. Modal properties of human fresh-frozen tibia (2)

Mode	Frequency (Hz)	Loss Factor	Modal Constant	Phase	Method
0	0.00	0.001	1.1621	11	Residual
1	389.31	0.094	1.6864	8	0-Fit
2	496.59	0.082	0.32207	-75	L-Fit
3	1200	0.001	0.82952	-63	Residual

In order to study the modal parameters of a dry tibia, an identical experiment is carried out on a dry tibia (tibia 3). The modal properties obtained are given in Table 3.

Table 3. Modal properties of human tibia (dry)

Mode	Frequency (Hz)	Loss Factor	Modal Constant	Phase	Method
0	0.00	0.001	45.276	0	Residual
1	526.09	0.011	18.328	-1	0-Fit
2	683.12	0.010	2.1585	-173	0-Fit
3	1449.61	0.013	207.06	-178	0-Fit
4	3750.00	0.001	495.10	-5	Residual

Comparing the modal parameters of the fresh-frozen and dry tibia specimens, two expected observations can be made. Firstly, the natural frequencies of a dry tibia are higher, compared to those of fresh-frozen tibia. Secondly, the modal loss factor of dry tibia is considerably smaller than those of fresh-frozen ones. Both changes are primarily related to the loss in mineral content and collagen of the bone. Then it is concluded that modal loss factor data can be a strong indicator of the mineral content and collagen of bones. Furthermore, having much larger percentage changes in the loss factors, compared to those in natural frequencies when mineral content and collagen are reduced, was an encouraging preliminary result to believe that damping measurements may yield a promising technique in diagnosing progressing osteoporosis and monitoring fracture healing period.

2.2. Modal Model of Tibia

A mathematical model for human tibia can be obtained by using the modal data identified (Tables 1-3). Regenerated FRF of tibia can be obtained by modal superposition of the modes identified as follows:

$$\alpha_{jk}(\omega) = \sum_{s=1}^N \frac{sA_{jk}}{\omega_s^2 - \omega^2 + i\eta_s\omega_s^2} \quad (1)$$

The comparisons of the regenerated FRFs with experimentally measured FRFs are given in Figures 4 to 6, for fresh-frozen tibia 1 and 2, and for dry tibia, respectively.

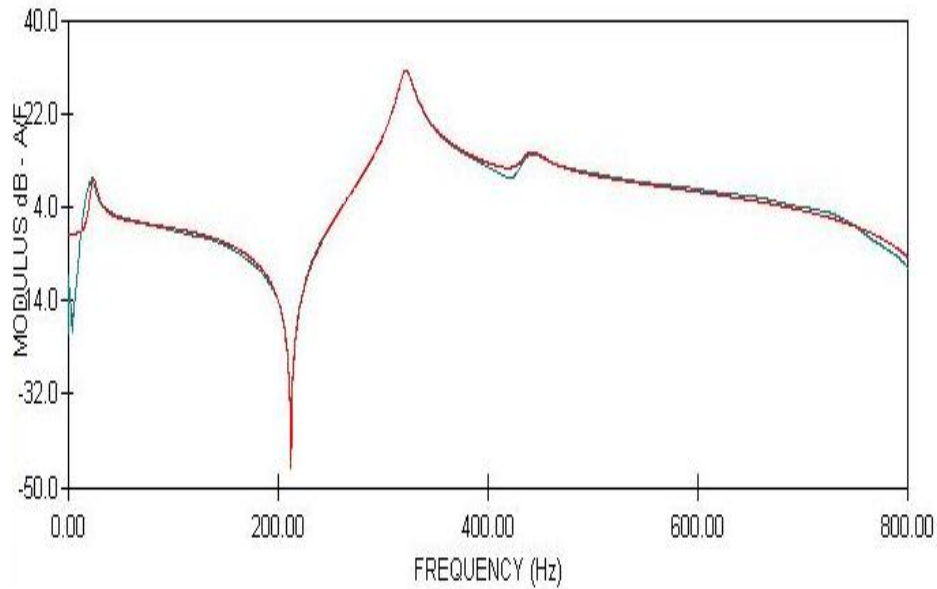


Figure 4. Regenerated FRF of First Test Specimen (fresh-frozen tibia 1)
Experimental FRF: green curve; Regenerated FRF: red curve

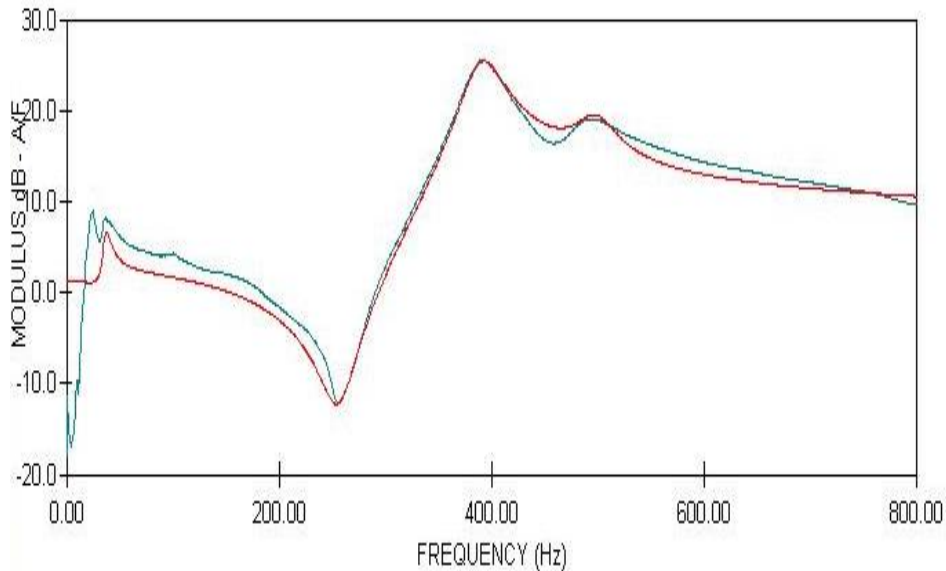


Figure 5. Regenerated FRF of Second Test Specimen (fresh-frozen tibia 2)
Experimental FRF: green curve; Regenerated FRF: red curve

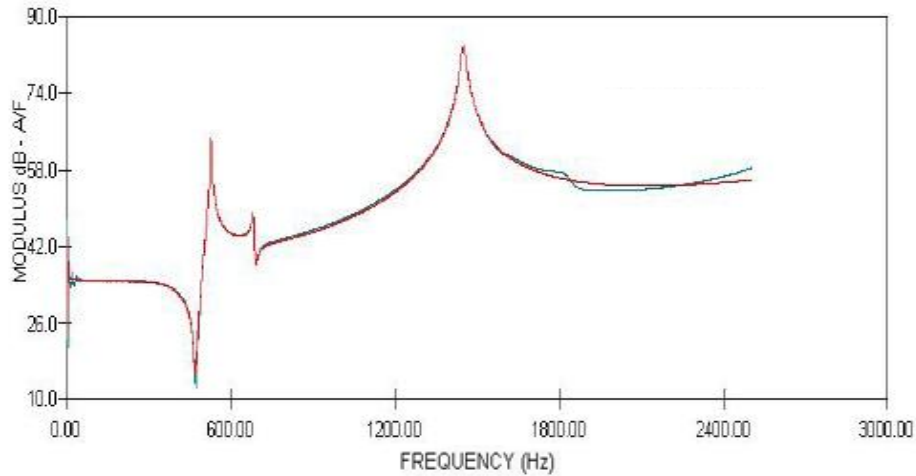


Figure 6. Regenerated FRF of Third Test Specimen (dry tibia)
 Experimental FRF: green curve; Regenerated FRF: red curve

From Figures 4-6, it is clearly seen that the regenerated FRFs perfectly fit the experimental ones. Furthermore, obtaining almost the same experimental FRFs for different forcing levels indicate that tibial bone show linear dynamic behavior, at least in the range of forcing levels used in the experiments.

3. PRELIMINARY IN VIVO EXPERIMENTS

Since the ultimate goal in this study is to perform in vivo tests in order to diagnose bone strength, a set of preliminary in vivo experiments were carried out. The aim in these tests was to observe the differences between experimental FRFs obtained by ex vivo tests and in vivo ones, in other words, to investigate the effects of the skin, muscles, joints and fibula on the FRF plot of tibia.

As the boundary conditions during the experiment are not expected to affect the modal damping ratio, rather than using free end conditions, the motion of both ends of the lower part of the leg is prevented in order to have better measurements. The in vivo experimental instrumentation is the same as the one used in the ex vivo case. The measurements are taken by holding and pressing the accelerometer at the measurement point, and manually pressing a small cylindrical metal element at the excitation point.

The in vivo FRF measurement results are shown in Figure 7. As can be seen from this plot, due to the damping introduced by skin and muscles, the FRFs are heavily damped, and seem in agreement with similar measurements given in literature [3, 8].

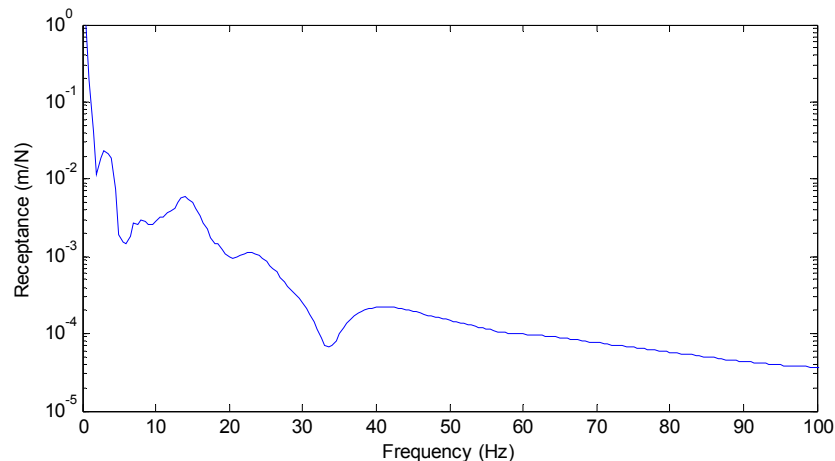


Figure 7. FRF plot of the tibia (in vivo)

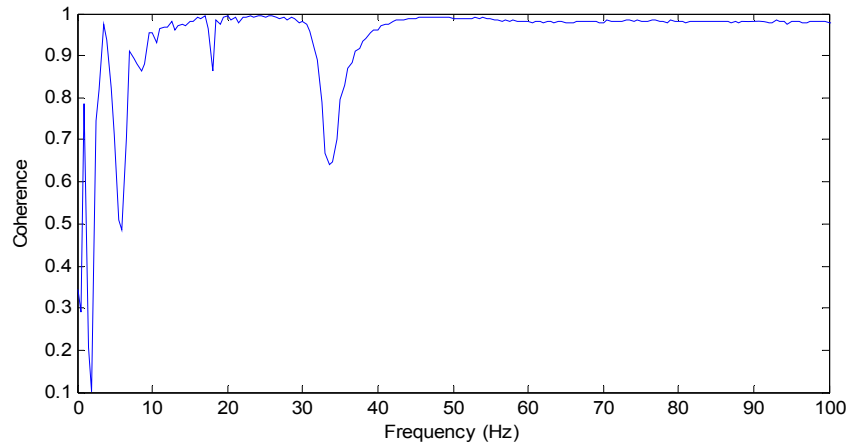


Figure 8. Coherence plot of the FRF measurements of the tibia (in vivo)

Plotting inertance graph instead of receptance, the modes can be seen more clearly. Figure 10 shows the inertance plot of the same experiment. Heavily damped nature of FRFs makes the modal identification difficult. Yet, the modal identification made by using MODENT[®] gave the modal loss factors around 0.2 for the first three modes as can be seen from Table 4. By using a simple theoretical discrete model, it is observed that even though the damping introduced by skin and muscles heavily dominate the modal loss factor, a change in the damping of the tibia will depict itself in the modal loss factor of the tibia-muscle-skin system that will be obtained from in vivo tests.

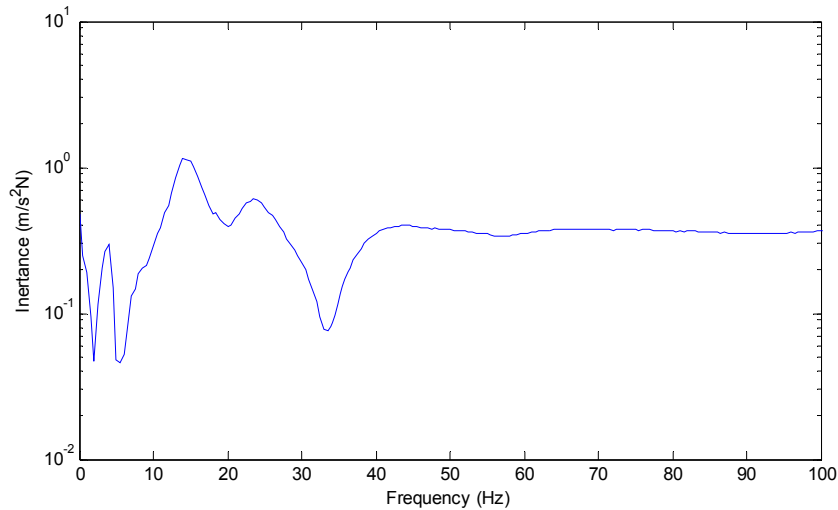


Figure 10. Inertance plot of the tibia (in vivo)

Table 4. Modal properties of human tibia in vivo

Mode	Frequency (Hz)	Loss Factor	Modal Constant	Phase	Method
0	0.00	0.001	0.16321	106	Residual
1	13.93	0.023	0.11837	-5	L-Fit
2	24.21	0.019	0.06736	-99	L-Fit
3	39.07	0.021	0.02897	34	L-Fit
4	150.00	0.100	0.33231	-117	Residual

4. CONCLUSIONS

In this paper the preliminary results of the study to diagnose osteoporosis from the in vivo frequency response function measurements of human tibial bone are presented. The previous studies using vibration measurements were generally based on the change of natural frequency with progressing osteoporosis to diagnose this metabolic bone disease. It is difficult to have success with such approaches since the natural frequencies measured do not depend only on the bone properties, but also on the geometry, dimensions and the boundary conditions during measurement. That makes the natural frequency an inconvenient parameter for the assessment of osteoporosis. However, damping measured as loss factor is an inherent property of bone, and therefore it is believed that it may be an alternative approach to detect progressing osteoporosis by studying the change in modal loss factor.

Firstly, experiments were carried out on two tibia specimens obtained from fresh-frozen cadavers with no history of metabolic bone disease or tibial fracture. The modal parameters identified from FRF measurements show that some differences can be observed both in the natural frequencies and loss factors of different specimens. It was expected to have differences in natural frequencies of two specimens, due to the reasons mentioned above. However, the modal loss factors of the specimens were expected to be closer to each other as DXA tests showed that the mineral contents of both tibiae were not much different. Then, these results may imply that modal loss factors of tibia are affected not only from the mineral content but also from the collagen which is the major organic component of the structure of bone. Yet, more specimens need to be tested to be able to generalize this conclusion.

Secondly, similar FRF experiments were carried out on a dry tibia, and the modal parameters were found to be considerably different from those of fresh-frozen tibia. These changes both in natural frequencies and loss factors are primarily related to the loss in mineral content and collagen of the bone. Having very large percentage changes in the loss factors when mineral content and collagen are reduced is an encouraging result to believe that damping measurements may yield a promising technique in diagnosing progressing osteoporosis and monitoring fracture healing period. However, the major difficulty in developing such a technique is observed in obtaining good in vivo FRF measurements from which reliable modal properties can be identified. This difficulty stems from the damping introduced by skin and muscles. Several different measurement techniques were tried to obtain good FRF measurements. Applying a preload by holding and pressing a small cylindrical metal element manually at the excitation point while holding the accelerometer during the excitation of the bone, as suggested in an earlier work [11], is found to be useful in decreasing the damping effect of the skin and the underlying soft tissue. The preliminary tests show that it is possible to identify modal loss factors from in vivo FRF measurements. When the modal loss factors in the order of 0.20 from the in vivo tests are considered in a purely theoretical model in which the modal damping of tibia itself is taken between 0.04 and 0.08, it is observed that a change in the damping of the tibia may still depict itself in the modal loss factor of the tibia-muscle-skin system that will be obtained from in vivo tests.

In conclusion, this study gives encouraging result to believe that damping measurements may be used in diagnosing progressing osteoporosis and monitoring fracture healing period. The study in progress includes in vivo tests on osteoporotic patients and comparing the results with those obtained from normal patients.

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