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Investigation of bone fracture diagnosis system using transverse vibration response

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Abstract

In this study, a new diagnostic system is developed to easily identify bone fractures in non-medical environments. It is difficult to determine the extent of cracks, fractures, and the healing process inside humans owing to the differences among people and limitations of state-of-the-art medical devices. Thus, various medical techniques, such as X-ray, computed tomography, or fork tuning systems have been developed, and more advanced technologies are emerging in the medical engineering field. In hazardous circumstances, medical devices to detect bone fracture are not available or cannot be easily applied. Thus, there is a need for the rapid detection of bone fractures without medical devices. To this end, this study analyzes the transverse vibration responses of bones because bone fractures cause different mechanical vibration reactions. By comparing the transverse vibration responses of both healthy and fractured bones, the modal assurance criterion can be calculated and applied to detect the existence of bone fractures. The transverse vibration responses at low and high frequencies are different and exhibit different modal assurance criteria depending on whether or not they are abnormal. Then, the virtual spectrogram of the differences between the signals from non-fractured and fractured bones is calculated. With the help of the present criterion with transverse vibration data, this difference can be analyzed quantitatively and effectively. To validate the proposed system, experiments with artificial specimens, animal legs, and a cadaver are performed.

Keywords

Transverse vibration, fracture, frequency response function, artificial bone, cadaver

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Introduction

The study employs information provided by low-frequency transverse vibrations to develop a new intelligent diagnostic system that identifies bone fractures and degenerative characteristics in non-medical environments. Various medical techniques, such as X-rays, computed tomography (CT), and fork tuning systems, have been developed and are widely used. In addition, more advanced technologies are currently emerging in the field of medical engineering[1–4] Radiography-based approaches, such as CT, X-Ray, electromagnetic interference (EMI), and positron emission tomography (PET)/CT are capable of accurately monitoring various pathological and trauma-induced conditions with some side effects. For the rapid detection of bone fractures without the need for radiation exposure, this research proposes the measurement and analysis of the transverse vibration responses of bones considering the bilateral symmetry of the human body. The presence of fractures in human bones results in different vibration responses. The size of fractures is often not significant, and they cannot be detected easily. This paper aims to develop an intelligent classification system that can detect and classify fractures. The developed system is comprised of two main stages. In the first stage, the transverse vibration responses of fractured and non-fractured bones are measured. Some related studies

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have found that the response varies depending on the presence or absence of fracture.[2,3,5–9] In particular, there are different responses at low and high frequencies, and this has also been observed in experiments. The present study develops an intelligent system to detect these characteristic responses and features.

There are several relevant studies that use vibration data to monitor patients. The clinical diagnosis of the bone fracture healing process has been researched previously.[10] In orthopaedists, the usage of a simple diapason or tuning fork to detect fracture is well known.[11] The study found that vibration-based diagnostics can be used to assess fracture healing, and that resonance frequency experiments can be used to estimate the strength of fracture bonds. The authors discussed the advantages of mechanical vibration analysis in terms of the use of a non-invasive methodology and the relation with mechanical strengths. The use of bilateral symmetry was also discussed, and the responses of the healing process were measured and discussed. A screening tool has been developed to detect long bone fractures in children.[3] It was observed that while most injured children were exposed to X-rays, the majority of cases showed the absence of fractures. Without the use of X-rays, doctors were unable to determine whether an injury was a sprain or a fracture. It was also reported that despite the low exposure to harmful X-ray radiation, the preference is for no radiation. A device called an intelligent bone fracture detection system (IBFDS) was developed.[4] Using X-ray images, a machine learning method comprising two conventional 3-layer back propagation neural networks (BPNNs) with 1024 input neurons was trained. A review of the application of AI systems to clinical decisions has been published.[12] An application of an AI system with two contour-based fracture detection schemes has been reported,[13] and the authors of this publication also used X-ray images. In total, 19 features could be extracted using their proposed approaches. Then, a clinical survey was conducted to estimate the value of the tuning-fork test to assess fractures in clinical practice.[2] This study concluded that the method has some merits in rural and remote settings. The transmission measurements of the ultrasonic waves propagating through simulated fractures have also been studied.[14] The authors conducted experiments and numerical tests to model the effect of fracture geometry. A vibration transmittance–based device (sternal vibration device (SVD)) has been proposed and developed to detect the early disruption of the sternal fixation.[5] An application of low-frequency vibration measurements was proposed in the field of orthopedics.[8] A low-frequency vibration study for the healing process was also discussed. The low-frequency vibration of animal bone with skin and muscle has been studied previously.[7] In order to satisfy the requirements of various applications, many studies related to bone fractures have been conducted using various techniques.

This paper presents a novel experimental method aimed at improving diagnosis ability using low-frequency transverse vibration data in order to quickly evaluate fractures and osteogenesis imperfection. In this method, after low-frequency responses are measured, Fourier transformations are performed to investigate the obtained time-dependent data in the frequency domain. The differences in the responses in the frequency domain present valuable information regarding the stiffness and strength of specimens. The bilateral symmetry provides healthy reference data for comparison purposes. A control-based algorithm is also applied to explore the potential for medical application. Here, it is important to determine how the responses to the unit force must be normalized, and the study proposes the use of a spectrogram (a representation of the spectrum of frequencies of a signal as it varies with time) of the Fourier transformed data. Furthermore, experiments are carried out using animal legs and cadavers to investigate the validity of the proposed method. After integrating all key technologies, a smart diagnosis system, as shown in Figure 1, was developed. The present study also tries to investigate the signal processing of the vibration signals to detect the fracture and present the usage of the bilateral symmetry. In addition, our observations indicate that the vibration data below 20 Hz are easily influenced by the boundary conditions and should be carefully interpreted.

The remainder of this paper is organized as follows. The next section discusses the phenomena of bone fracture. Then, the experimental methodologies are discussed, and the intelligent diagnosis system is proposed. Subsequently, experimental results obtained using artificial specimens, animal bones, and a cadaver are presented. Results obtained from several tests, including a cadaver test, are presented to validate the present approach. The final section concludes the paper.

Fracture and degenerative condition detection

In this study, an intelligent classification system for bone fractures or degenerative conditions using low-frequency transverse vibration data was developed, as shown in Figure 1. Diagnostic systems that are based on vibration analysis have the advantages of being non-invasive and relatively inexpensive. The vibration analysis involves exciting the human body mechanically, as well as acquiring and analyzing force input and acceleration output signals. By acquiring vibration information on various factors that are influenced by fractures, it is possible that degenerative medical conditions such as fractures, cracks, osteoporosis, or joint loosening can be diagnosed. In existing intelligent systems, the impulse force is generated by a hammer impact on bones or tissues, and the steady state vibration is measured using an accelerometer with a DAQ device, as illustrated in Figure 2. The effect of muscle

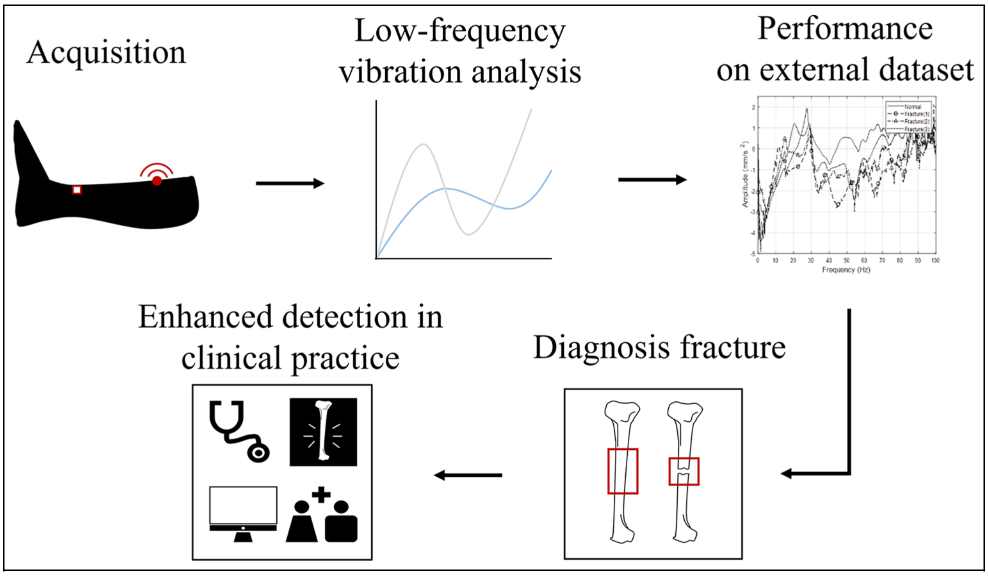

Figure 1. Diagnosis system with low-frequency vibration.

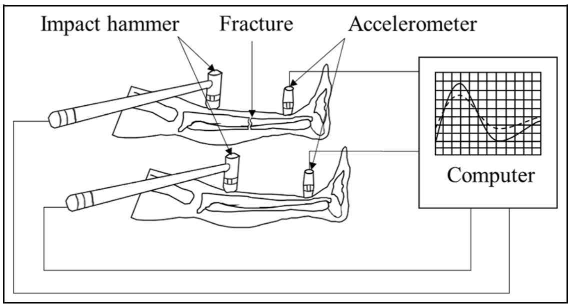

Figure 2. Data acquisition device (Impact hammer (transverse force) and acceleration (transverse vibration)).

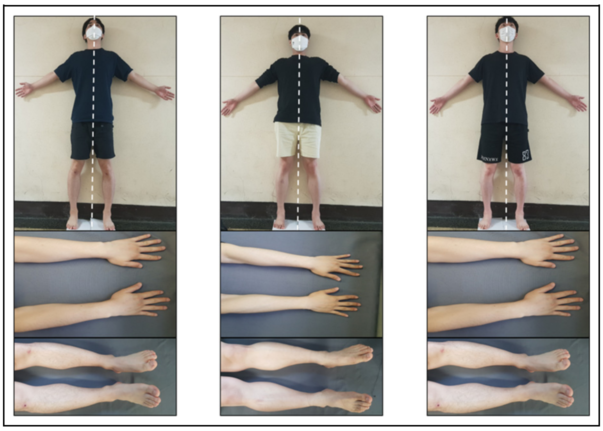

Figure 3. Bilateral symmetry of three persons (With some differences, similar behaviors can be observed owing to bilateral symmetry).

and skin on the vibration is also tested, and the features are extracted. As stated, to create reference data, bilateral symmetry is considered in the measurement system; the reference signal is measured on the other side. To rigorously separate the signals, a control-based algorithm is also developed.

Mechanical aspects of fracture and degenerative conditions

Degenerative conditions such as fractures, tissue damage, and complex cracks can be detected using medical X-rays or CT image processes in well-equipped hospitals. However, low-cost point-of-care is also essential in the treatment of such conditions in order to improve healthcare in developing regions and during hazardous situations such as wars, protests, and extreme exercises. Based on relevant previous studies, it is found that low-frequency vibration data in the range of 100 Hz–250 Hz can be used by medical professionals to diagnose degenerative conditions, particularly fractures, and healing processes, followed by pathological conditions. The vibration response of some complex bone fractures can be modeled from a mechanical perspective. Depending on the type of fracture, some debris can appear around the fracture section, and complex cracks can form. This research aims to model these medical conditions using a simplified engineering model. For example, when a bone fractures or cracks, the static stiffness becomes lower, and the bone weakens. The skin, vein, and muscle surrounding the bone are the only intact support structures. Thus, in addition to the static response, the displacements at higher frequencies are also affected. Owing to the viscoelastic or viscoplastic properties of humans, it is intricate to quantitatively evaluate and predict the responses of humans. Low-frequency vibration data can be modeled ignoring these complex aspects.

Bilateral symmetry (Body symmetry, biological symmetry) and fracture detection

To determine if a fracture has occurred, some reference vibration data should be measured in advance. One of the limitations of the vibration-based diagnosis approach is that there is a need for some reference data that are not required for the diagnosis methods based on radiographs. It can be easily observed that the static and dynamic stiffness of fractured bone decreases compared with that of healthy bone, as shown in Figure 1. However, owing to the differences in size, age, and sex of humans, it is difficult to quantify these variations. In addition, variations in the static and dynamic material properties with different conditions present additional challenges. Depending on the height, activity, or mental/physical condition of people, the mechanical responses to impact force, that is, forced vibration, vary at every instant. These differences can be considered within a controlled laboratory, but it is challenging in hazardous situations. Thus, to create a reliable diagnosis system, it is crucial to possess reference data.

This paper proposes the use of bilateral symmetry, which is sometimes called mirror symmetry, to address this issue. The bilateral symmetry of humans can be observed. Although small differences in strength are inevitably observed, the human body exhibits almost the same mechanical properties along with the bilateral symmetry; disabled persons are not included in the scope of this research. In the absence of any significant prior injury, similar size and material properties are observed for arms, legs, and chest, as shown in Figure 3. With the same sensors and actuators, the mechanical vibrations at parts that exhibit bilateral symmetry can be measured and compared to diagnose serious fractures. One of the practical advantages of this concept is that it is robust in terms of the actuation positions and measurement position; it is sufficient to locate suspected locations of fractures between the same actuation positions and measurement positions.[8] Using bilateral symmetry, the conditions of the human body can be enhanced without prior knowledge about the human conditions; the accumulated data can also be used and customized. To analyze and classify diagnostic signals from humans, signals from both sides of a human with bilateral symmetry are measured and analyzed using a smart diagnosis system.

Smart diagnosis system: Modal assurance criterion

It is important to distinguish between signals that indicate no medical issue and signals indicating some degenerative problems or fracture. This research shows that by treating the FRF signals as modes, it is possible to compute the MAC values of the FRF signal with or without fracture, and that the MAC criterion can be used to quantify the difference.

The MAC criterion is newly interpreted as a measure to identify the existence of fracture in this research. The MAC is a statistical indicator sensitive to large differences and relatively insensitive to small differences in mode shapes.[15] In this research, the application of the MAC criterion means the identification of the existence of fracture in bone specimen. First of all, the transverse accelerations of a suspicious bone specimen and the bone specimen confirmed not fracture are obtained using the bilateral symmetry for example. Adjust the suspicious spots between the locations of the actuator and impact hammer to get the acceleration responses. After that, the frequency response functions of the transverse acceleration signals are obtained through the fast Fourier transform. The fast Fourier transforms are carried out using the command "FFT" in MATLAB. Although they are eligible to be used to identify the existence of fracture through eye inspection, the effects of the damping from muscle and the uncertainty from human body and experiment environment should be filtered and this research proposes to use the frequency response functions below approximately 150 Hz and above 20 Hz. Then, this research suggests regarding or treating the frequency response functions at the specified frequency domain as some vibration modes. Although the employed eigenmodes of the MAC criterion should be orthogonal, this research founds that the concept of the MAC criterion can be extended to be used as a statistical indicator to identify the difference of the signals of interest. Specifically, it is regarded that the suspicious specimen has a high possibility to contain fracture when the MAC value with the signals of a healthy specimen becomes a small value. On the contrary, the suspicious specimen can be regarded as a specimen without fracture when the MAC value becomes near one. The experiments prove the potential applicability of the MAC criterion as a measure to identify the existence of fracture. Another approach is to investigate the characteristics of the signals using a spectrogram of the variations in the frequency response function with the transverse vibration data, and to classify them based on the detected features. The virtual spectrogram is used to identify the existence of fracture in this research. Spectrogram is a two-dimensional visual representation of the frequency spectrum of a signal that varies over time. This study calculates the virtual spectrogram with the differences of the FFT curves. To achieve this, first of all, the transverse accelerations are obtained by a bone specimen suspected of fracture and the bone specimen confirmed not to have fracture. The measured accelerations are transformed into the frequency response functions through Fast Fourier transform. After that, the spectrogram for the difference of the transformed response functions is calculated, that is, the virtual spectrogram. If the two bone specimens have no fracture, the difference in the frequency response functions would be close to zero. On the other hand, the difference will be large and the virtual spectrogram will identify the difference. Thus, the virtual spectrogram is used as a method to visually determine the presence or absence of a bone fracture.

The representative curves of transverse vibration of fractured and non-fractured bones, as shown in Figure 4(a), should be distinguished. Regardless of the presence or absence of fractures, the vibration signals oscillate and decay owing to the damping caused by muscles

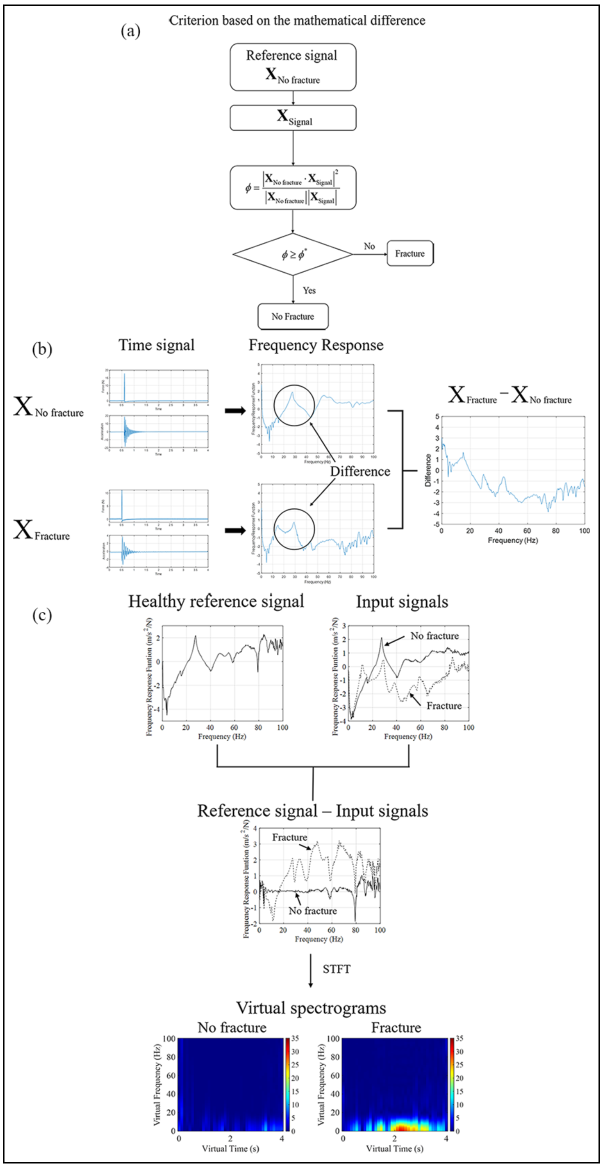

Figure 4. (a) Determination process based on the modal assurance criterion (MAC), (b) the difference of the signals, and (c) the process of the virtual spectrograms.

and blood. In the presence of fractures, additional oscillations with other frequencies are observed in the frequency response function. Frequency domain analysis was used to identify signals originating from fractures or cracks. To distinguish these signals and determine the existence of fractures or cracks, this research also investigated signals in the frequency domain (Fourier transformation) and proposed the use of the MAC given in (1) by interpreting the frequency response curves as the signal vectors.[15] To this end, we must predetermine the frequency range of the curve for the evaluation of ϕ in (1). Based on previous relevant studies and experiments in the present study, we set the maximum frequency value in the range of 60 Hz–100 Hz; the frequency response function curves from 20 Hz to the maximum frequency are used to compute ϕ. We observed that the responses below 20 Hz are not reliable owing to uncertainty in the boundary condition. With this approach, the algorithm presented in Figure 4(b) can be implemented. Determining the maximum reference value that is required to efficiently classify signals is another challenge. The original spectrogram analysis is based on the short time Fourier transform for the diagnosis of time varying signals. In our study, the new spectrogram analysis is defined to interpret the frequency response functions as shown in Figure 4(c). In the next section, we present the experiments that we conducted to determine this value. Note that the reference signal is obtained using bilateral symmetry. The aforementioned criterion can be applied for the separation of the signals with and without fractures using the criterion value of $\phi > \phi^*$.

$$\phi = \frac{\left|\mathbf{X}_{\mathrm{Nofracture}} \cdot \mathbf{X}_{\mathrm{Signal}}\right|^2}{\left|\mathbf{X}_{\mathrm{Nofracture}}\right|\left|\mathbf{X}_{\mathrm{Signal}}\right|} \tag{1}$$

where the reference signal, $\mathbf{X}_{\mathrm{Nofracture}}$, is the signal without any fracture, and the signal of interest is denoted by $\mathbf{X}_{\mathrm{Signal}}$. Using the above formulation, the difference between the two signals can be evaluated. Our proposition is to investigate this value to determine if the bone of interest is problematic, as shown in Figure 4(a). The evaluation procedure is outlined below.

$$\begin{aligned} &\phi \geqslant \phi^* \text{No problem(No fracture or no degenerative bone)} \\ &\phi \leqslant \phi^* \text{Problem(Fracture or degenerative bone)} \end{aligned} \tag{2}$$

where the critical value is denoted by ϕ^*. In this process, determining the frequency range of the involved signals as well as the maximum value ϕ^* is challenging. As the orders of magnitude of the length and density of human bone are similar, the frequency ranges of the signals containing fracture information are similar, and this study considers signals below 100 Hz. In addition, the lower bound of the frequency range should be considered owing to the different boundary conditions. Determining the criterion value is also an issue and should be done heuristically. Detailed examples are discussed in the next section.

Experimental methodology

In order to validate the proposed method, three types of experiments were conducted to obtain vibration responses, as shown in Figure 5. First, test specimens were fabricated using a combination of plastic rods and silicone to mimic muscle and skin. The silicone and curing agent (hardener) were mixed in a ratio of 100:3 and then cured to form a specimen. The larger the proportion of hardener, the harder is the silicone. The plastic rod was cut in the middle to mimic a fracture. One end of the plastic test specimen was clamped. After the rods with and without the fractures were coated with

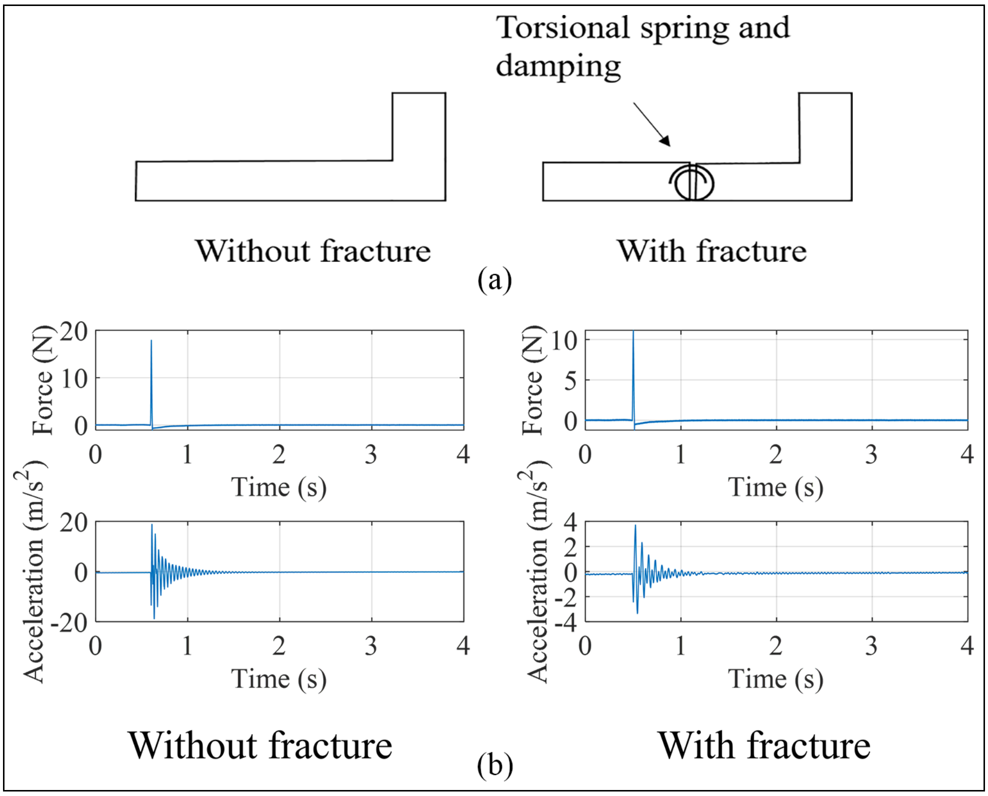

Figure 5. (a) Simple models of fractured bone with torsional spring and damping and (b) representative force and acceleration curves of artificial specimens with and without fracture.

silicone, the specimens were stored for 1 day to stabilize the material properties. The purpose of this artificial bone experiment was to investigate the effect of artificial fractures on low-frequency vibration responses. However, this experiment was limited as it considered only single fractures as opposed to complex fractures. Second, test specimens of the leg bones of animals (pigs) were prepared. The middle part of one bone was cut, and healthy bone specimens of the same size and area were prepared to obtain a reference signal using bilateral symmetry. For ease of clamping, a cube gypsum box was fixed to the end of the animal bone and used as a jig. Finally, an experiment using a cadaver with a leg fracture was performed. In the cadaver experiment, it was revealed that the boundary condition affects the responses, and it is necessary to determine the frequency range of interest. This experiment revealed that the frequency responses below the 20-Hz low-frequency band are affected. Thus, there is an optimal frequency range in which the fracture must be analyzed, that is, above 20 Hz and less than 100 Hz.

An impact hammer was used to apply the force, and an accelerometer sensor was attached to the other side of the bone to measure the acceleration. Experiments with fractured and non-fractured bones were performed simultaneously to ensure that similar environmental conditions in terms of temperature and moisture can be maintained during the experiments. Low-frequency vibration signals were recorded using a DAQ device. For the experiments, the accelerometer (PCB 352C33) and the hammer (PCB 086C03) are employed. The NI-9234 DAQ device is used for data acquisition. The sampling rate was set to 51200. Several pretests were carried out to ensure the consistency of vibration data. Signal processing with fast Fourier transform (FFT) was performed in MATLAB. In addition to the FFT, spectrum analysis, that is, short-time FFT (SFFT), was also performed.

Results and discussion

Experiments with artificial specimens (plastic rod and silicon specimen)

Figure 6 presents the two specimens with plastic rods for bone substitute and silicon for muscle and skin replacement. Although several differences are observed in the mechanical properties of these specimens compared to those of bone and muscle, the mechanical vibration properties are similar compared with those of bone and muscle, and they can be used to study the mechanical responses of complex porous scaffolds. Representative time vibration signals are provided in Figures 5(b), 6(b) and (c). The impact force was applied and the acceleration was measured at the other side, with one side fixed. Figure 6(b) shows the acceleration response of a direct impact on a plastic rod, and Figure 6(c) shows the acceleration response of a direct impact

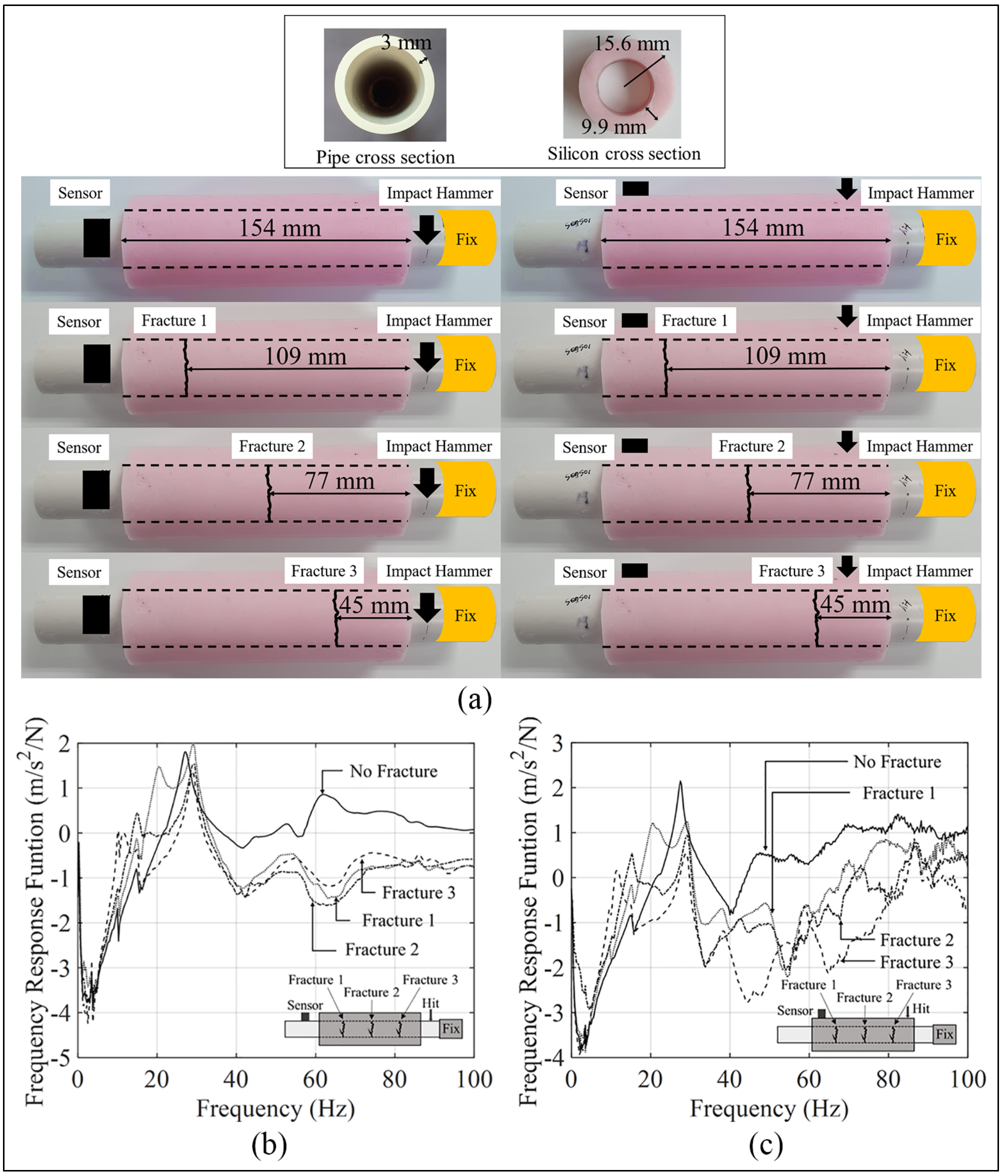

Figure 6. Experiments with plastic bar and silicon (in the graph, the *x* and *y* coordinates represent the number of experiments; here, 20 tests were conducted each for non-fractured and fractured specimens): (a) specimens with and without fractures or cracks, (b) responses with the sensor and the actuator attached to the surface of the plastic bar, and (c) responses with the sensor and the actuator attached to the surface of the viscoelastic silicon (The effect of the viscoelastic material can be observed compared with the response in (b)).

to the silicon. Noticeably, compared with those with fractures, the displacement responses of the specimens without fractures are lower below the resonance frequency associated with the bending mode at around 30 Hz. The responses with the fractures show lower acceleration values, and the resonance frequencies proportional to the square root of the stiffness are below the resonance frequency without the fracture. This indicates that the stiffness of the plastic rod with the fracture or crack is smaller. The resonance frequencies with the highest accelerations are similar to the bending modes. However, the acceleration responses with the fractures markedly decrease after the first bending mode up to 100 Hz, compared to the case without the fracture. The magnitudes of the responses with and without the fracture are similar to those of the impact test in Figure 6. After the first frequency with the largest amplitude, some complex responses are observed in Figure 6(b) and (c). The results verify that the acceleration with the fracture is less than that without the fracture. To understand this, the schematic models in Figure 5 can be considered. It is possible to interpret the fracture using torsional spring and damping. From a physical perspective, owing to the fracture and the associated loss of stiffness, the vertical displacements increase. A comparison of the two sets of results indicates that the vibration signal with the fracture has a lower amplitude after the bending resonance frequency owing to the damping and a lower resonance frequency. The effect of the soft tissue is important and

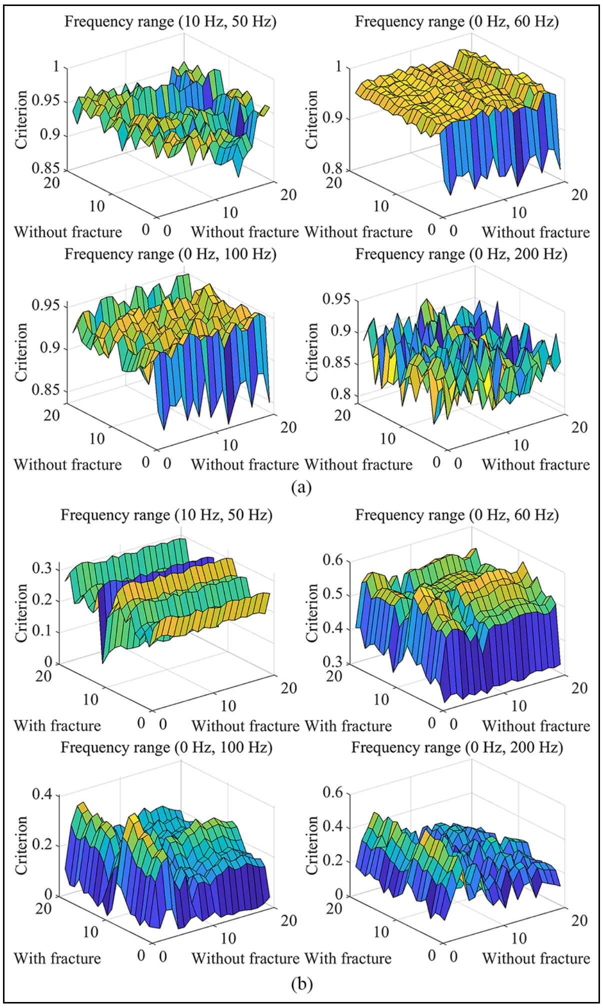

Figure 7. Illustration of the MAC-based criterion (the x and y coordinates represent the number of experiments; here, 20 tests were conducted each for non-fractured and fractured specimens): (a) MAC values (no fracture × no fracture) and (b) MAC values (fracture × no fracture).

the responses with and without soft tissue will be different as shown in Figure 6(a) and (b); the left sides are the experiments with the accelerometer and the impact hammer at the plastic bar and the right sides are the experiments with the accelerometer and the impact hammer at the rubber. High-frequency vibrations are easily attenuated by viscoelastic materials such as skin and muscles, but not much to low-frequency vibrations. The stiffness effect of soft tissue modeled with viscoelastic materials is increased at low frequency vibrations. In the cadaver experiment, the soft tissue is relatively thin. The present smart diagnosis system captures these characteristics of the curves with or without fractures.

To apply the MAC-based criterion in (1), several issues should be discussed and resolved. First, the frequency range for the MAC criterion should be determined. Considering the signals of these tests, this study proposes using transverse vibration signals below 100 Hz, which are suitable for characterizing the vibration signals. In addition, the criterion value of the MAC-based criterion should be determined. Figure 7 shows the curves of the MAC values for several specimens with and without fractures. The responses of the bone without fracture are regarded as reference signals. Figure 7 compares the responses with different frequency intervals. The figure also shows the consistency of the responses. Considering the curves and the distributions of the MAC values in Figure 7, this study proposes to adopt a real value between 0.4 and 0.5. The boundary condition also should be considered in these kinds of studies. For example, in the above experiments, the one ends of the fractured and unfractured bars are clamped and their responses are measured and compared. However, it is possible for a patient to lay down on the ground for the comparisons of their responses. For example, Figure 8 shows the response of the same specimens on the ground and their MAC values. As illustrated, the responses are changed dramatically and the MAC criterion can be used to identify the existence of fracture. In short, the MAC value can be used to identify whether or not a bone has fracture.

In addition, Figure 9 shows the differences between the signals and the reference signal (the responses without the fracture). Figure 9(a) (the vibration without fracture) presents the reference signal. Figure 9(b) shows the difference curves of 20 datasets of the specimens without the fracture, and Figure 9(c) shows the difference curves of 20 datasets of the specimens with different fractures. The feature observed in Figure 9(c) can be used to identify the fracture location. Figure 10 shows the spectrogram of the data in Figure 9. To draw these figures, three specimens with the center fracture are prepared for Figure 10(b), (c), and (d). To obtain the responses in Figure 6, the averaging scheme for independent data is applied to reduce the measurement errors. The MAC criteria in Figure 7 are the computed data with the individual data before the averaging scheme. The data in Figures 9 and 10 are based on the averaged FRF. The other results are also obtained with the same approach. For future research, it is expected that these figures can be used for the application of the deep learning algorithm.

The virtual spectrograms which are the short time Fourier transforms of the differences of the frequency response functions of the reference model and an unknown model can be incorporated with the deep learning algorithm. For example, the virtual spectrograms of the 10 fractured and 10 unfractured plastic pipe specimens in Figure 11 are obtained. Then, the CNN (Convolutional Neural Network) of the matlab toolbox can be trained with the 20 virtual spectrogram images.[16] Figure 11(b) shows the confusion matrix showing the accuracy of the trained CNN network. In this particular example, 100 percent accuracy can be achieved with this CNN algorithm. This example shows the potential application of the virtual spectrogram. In order to apply this concept to human, some data should be accumulated. Due to the limitation of the cadaver data, it is impossible to apply this

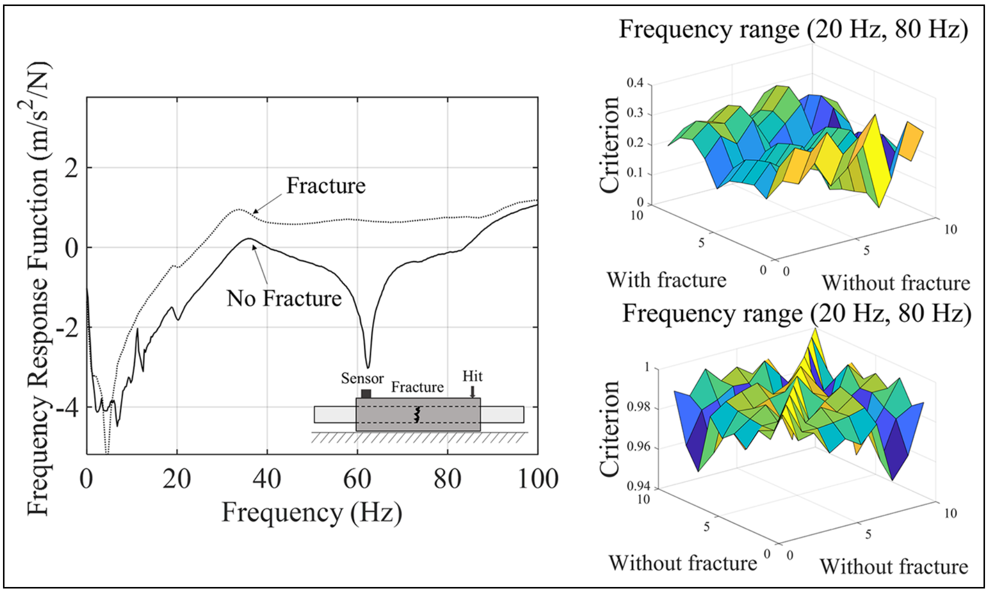

Figure 8. Illustration of experimental results of plastic bar and silicon on ground (the boundary conditions are changed). MAC values at the top (fracture × no fracture) and MAC values at the bottom (no fracture × no fracture).

technique for the cadaver case. Indeed, a further research is required for the data argumentation in the deep learning algorithm.

Experiments using pig legs

Pig legs with or without fractures were prepared to expand the previous study and to verify the low-frequency vibration characteristics observed with artificial specimens in Figure 12. Experiments were conducted using the artificial specimens in Figure 6. The experiment was performed to determine the responses of animal bone with and without fracture. Experimental mock-ups of pig legs with and without a central segment of changing stiffness were prepared. The length is approximately 20 cm, and a fracture was made in the middle of the bone. At one end of the animal leg, a gypsum box was attached to apply the clamp condition. After solidifying the gypsum, the impact hammer tests were carried out using the same equipment in Figure 6, similar to that in the case with artificial specimens. In the artificial specimens, the main resonance frequency is observed at around 30 Hz. In this leg experiment, the main resonance frequency is observed at around 10 and 50 Hz. For the bone with fracture, the acceleration is high before the main resonant frequency, and the acceleration response then decreases thereafter. This phenomenon is also observed in artificial specimens and can be useful to determine the diagnosis of fracture or degenerative symptoms. The present smart intelligent system relies on the differences in the responses. Figure 13 shows the MAC values. Owing to the limitations of the experiment involving the animal bone, only four experiments were performed. Figure 14 shows the differences between the vibration signals and the reference signal (no fracture). As shown in this figure, the differences increase with the fracture. Figure 15 shows the virtual spectrograms that were obtained using the signals in Figure 13. For the artificial specimens, clear differences are observed with the virtual spectrograms. By considering the MAC values and the virtual spectrograms, the existence of the fracture can be verified.

Experiments using a cadaver

As a final experiment, a cadaver (male, 84 years old, 168 cm tall) was prepared in an anatomy laboratory in Hanyang University, Seoul, Korea, on July 2020. To verify the concept of the low-frequency transverse vibration, the tibia of one side of the cadaver was cut to simulate the fracture situation. The fracture using a bone saw was made on the midpoint between the tibial tuberosity and the medial malleolus. During the experiment, as the body is placed on the table, the boundary condition of the legs can be considered a boundary condition on which people are placed on the ground. In addition, note that the muscle works as the damping condition to the transverse vibration. Figure 16(a) shows the experimental setup of the cadaver. The sensors are placed (on 10 cm distal from the fracture), and the force is applied (on 10 cm proximal from the fracture). Figure 16(b) shows the responses with and without fracture. In this experiment, the response curves are similar to those of the artificial specimens and the pig legs. The first natural frequency with the fracture is lower than that of the intact leg. The responses are higher than those of the intact bone near the first resonance

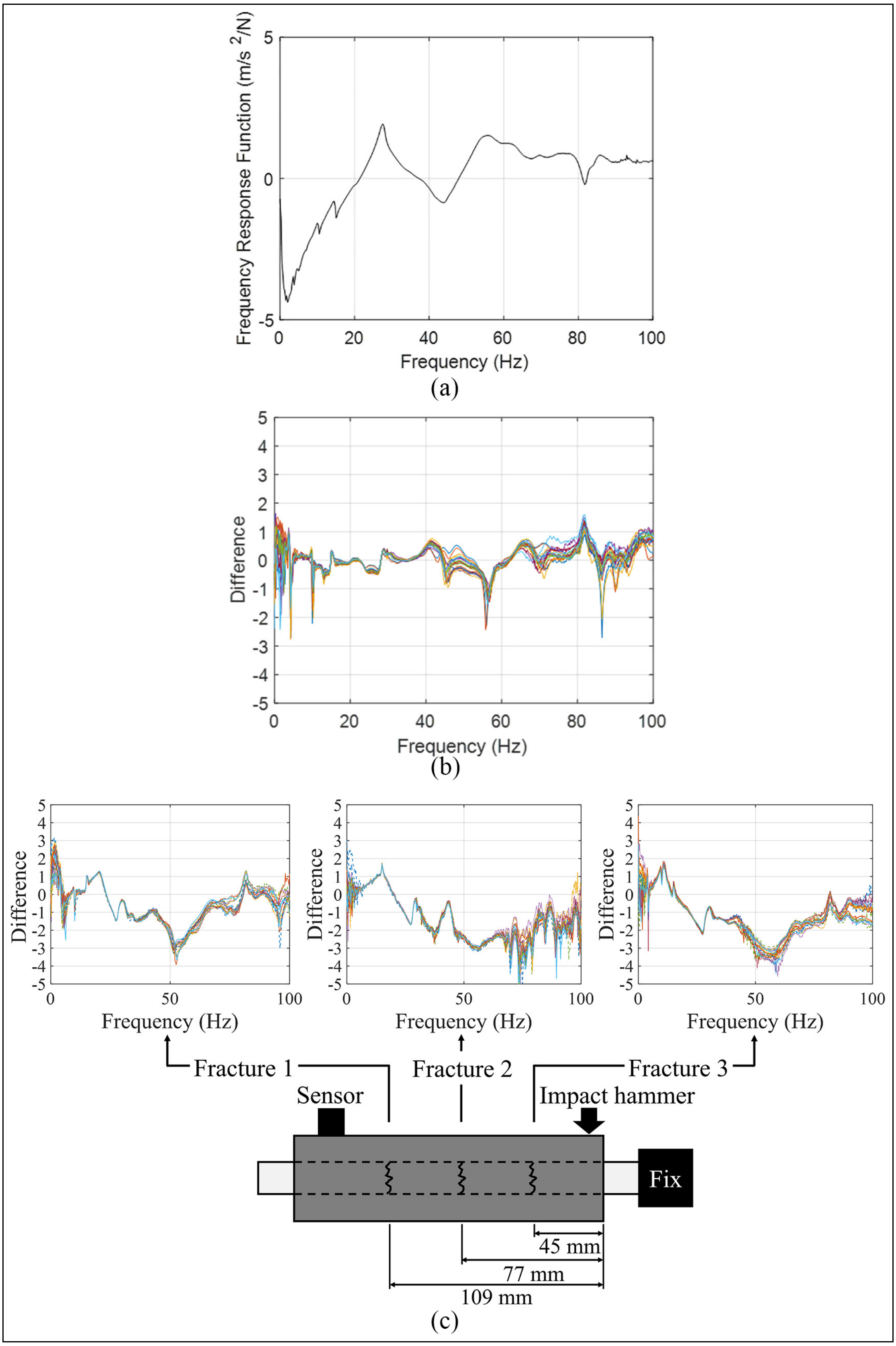

Figure 9. Plots showing differences with the reference signal without fractures: (a) reference signal without fractures, (b) 20 difference curves (the FRF signals without the fracture – the reference signal), and (c) 20 difference curves (the FRF signals with fracture – the reference signal).

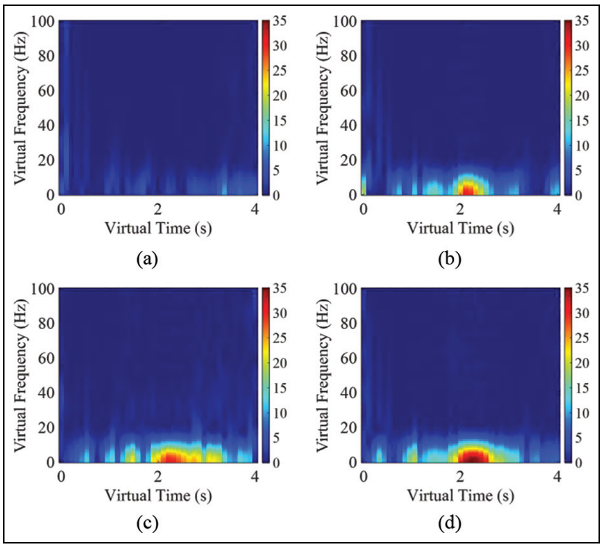

Figure 10. Virtual spectrogram with plastic bar and silicon experiment (the sensor and the actuator attached to the surface of the viscoelastic silicon): (a) spectrogram of the differences of the responses without fracture, (b) spectrogram of the differences of the responses with fracture (specimen with Facture 1) and those without fracture, (c) spectrogram of the differences of the responses with fracture (specimen with Fracture 2) and those without fracture, and (d) spectrogram of the differences of the responses with fracture (specimen with Fracture 3) and those without fracture.

frequency. Then, the responses at higher frequencies increase after the fracture. This final experiment using a cadaver verifies the usage of the transverse vibration to detect fractures. Considering the responses in Figure 16(b), the modal assurance criterion values of 20 sets of response data in the frequency range from 20 Hz to 60 Hz are calculated in Figure 17. In the cadaver experiment, the maximum criterion value observed in the experiments with the plastic rod and the pig leg is also about 0.5. Figure 18(a) shows the reference signal for the intact bone case, and Figure 18(b) shows the differences between the transverse vibration signals of the intact leg and the reference signal. In these figures, several differences are observed in the lower frequency range less than 20 Hz. Between 20 Hz and 60 Hz, almost identical signals are obtained. Figure 18(c) shows the differences between the transverse vibration signals of an intact leg and the signals of the fractured leg. Several differences are observed for all of the frequency ranges, which illustrates the validity of the present concept of the usage of the transverse vibration signal to detect the fracture. Figure 19 shows the spectrograms of the data, which illustrate the concept of the spectrogram.

In the controlled and organized experiments with artificial and animal specimens, the lower limit of the frequency range can be set to 0 Hz. However, the systematic and controlled boundary conditions considering

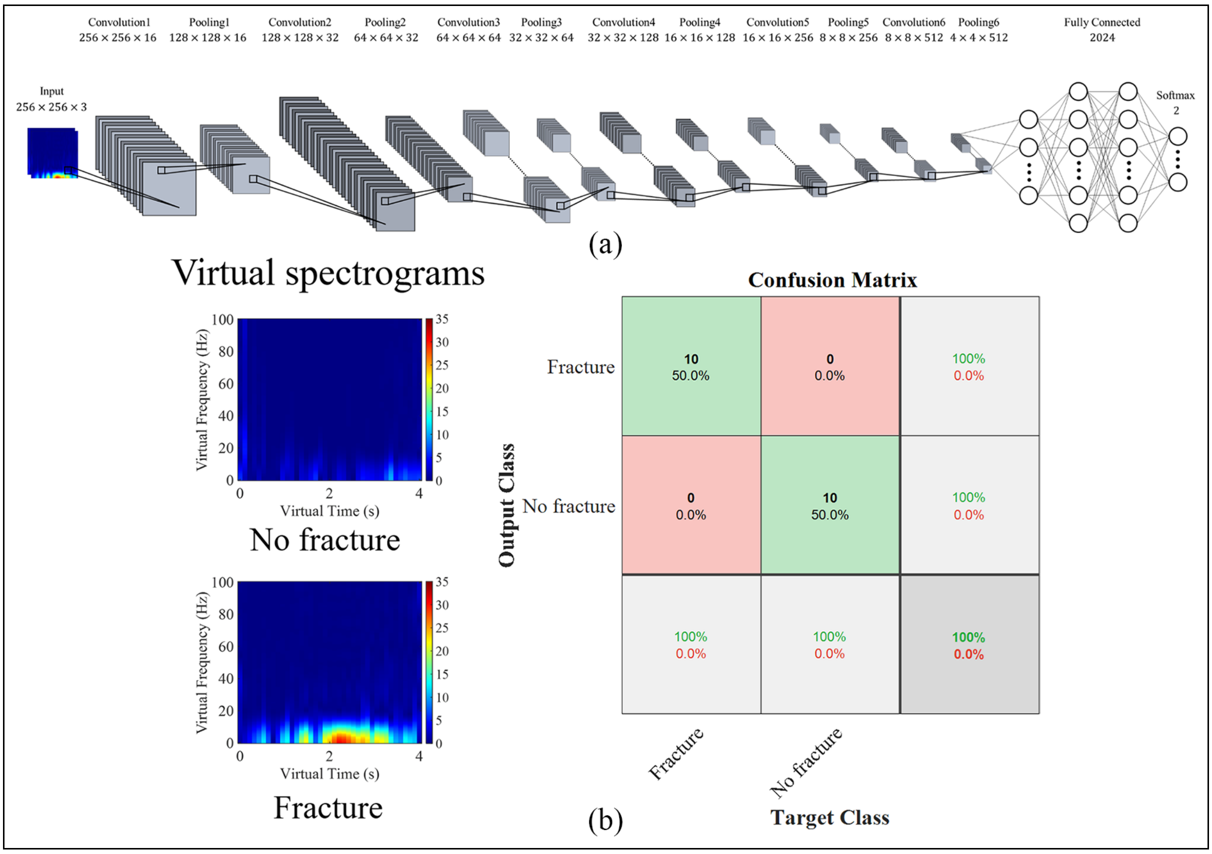

Figure 11. (a) The CNN architecture (size of input image: 256 × 256 × 3, epoch: 20, learning rate: 0.0001, softmax: 2, six convolutional layers and pooling layers) and (b) the confusion matrix of CNN in the classification of fracture.

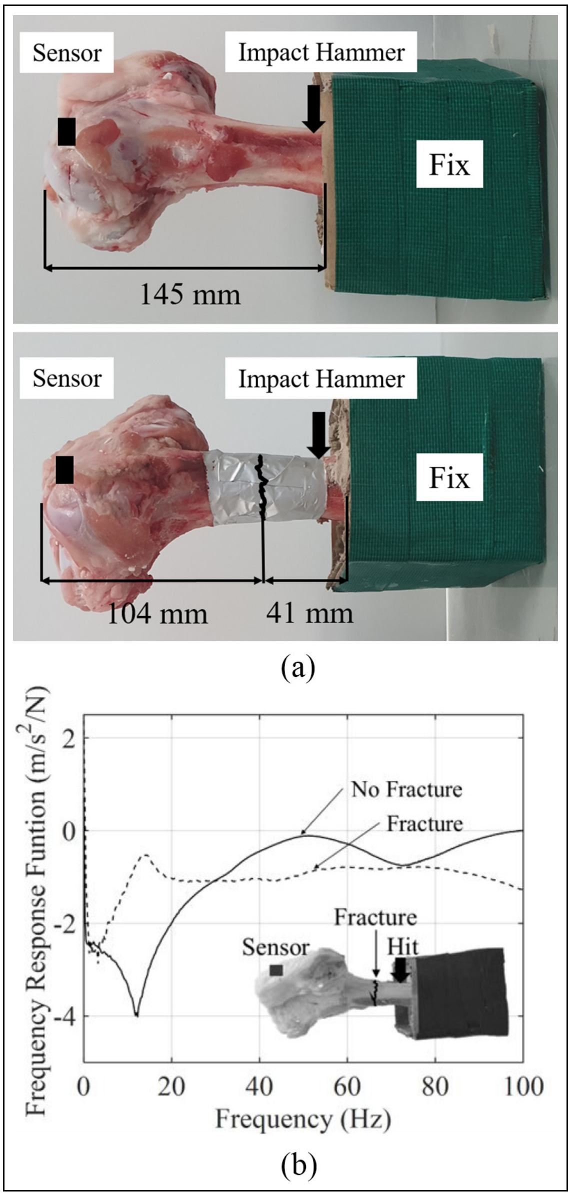

Figure 12. Experiment with pig legs: (a) pig legs with and without fracture and (b) the frequency response functions.

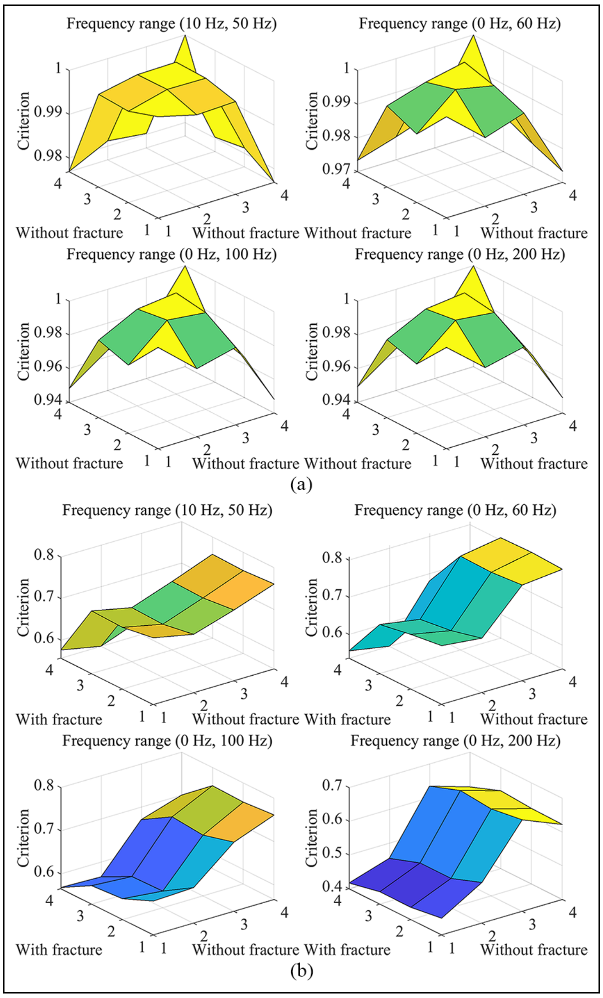

Figure 13. Illustration of MAC-based criterion with the pig legs (the x and y coordinates represent the number of experiments; here, four tests were conducted each for non-fractured and fractured specimens): (a) MAC values (no fracture × no fracture) and (b) MAC values (fracture × no fracture).

the bilateral symmetric condition cannot be imposed for experiments that involve dead or living human bodies. Therefore, in diagnostic systems, it is necessary to use with caution frequency response data below about 20 Hz. As a final remark, the deep learning algorithm can be incorporated with the virtual spectrogram with the help of the data argumentation in future.

Conclusions

This study provides an important contribution to the development of knowledge-based basic medical devices that monitor bone fracture or degenerative conditions using low-frequency transverse vibration signals. While the present approach cannot replace precise medical diagnostics devices using X-rays or other approaches, it is a potential alternative for diagnosing suspected underlying bone disease in developing areas or in hazardous environments without the need for exposure X-rays based on low-frequency vibration signals and the MAC-based criterion. By performing various experiments, the observations about the low-frequency vibration made from other relevant studies were reconfirmed. With fractures, the first resonance frequency decreases as the stiffness value decreases with fractures. The transverse vibration responses with fractures are higher than those with fractures after the first representative resonance frequency. To validate this and to demonstrate the quantitative differences, several experiments were carried out using plastic rods, pig bone, and human bone (cadaver). Based on the results of the

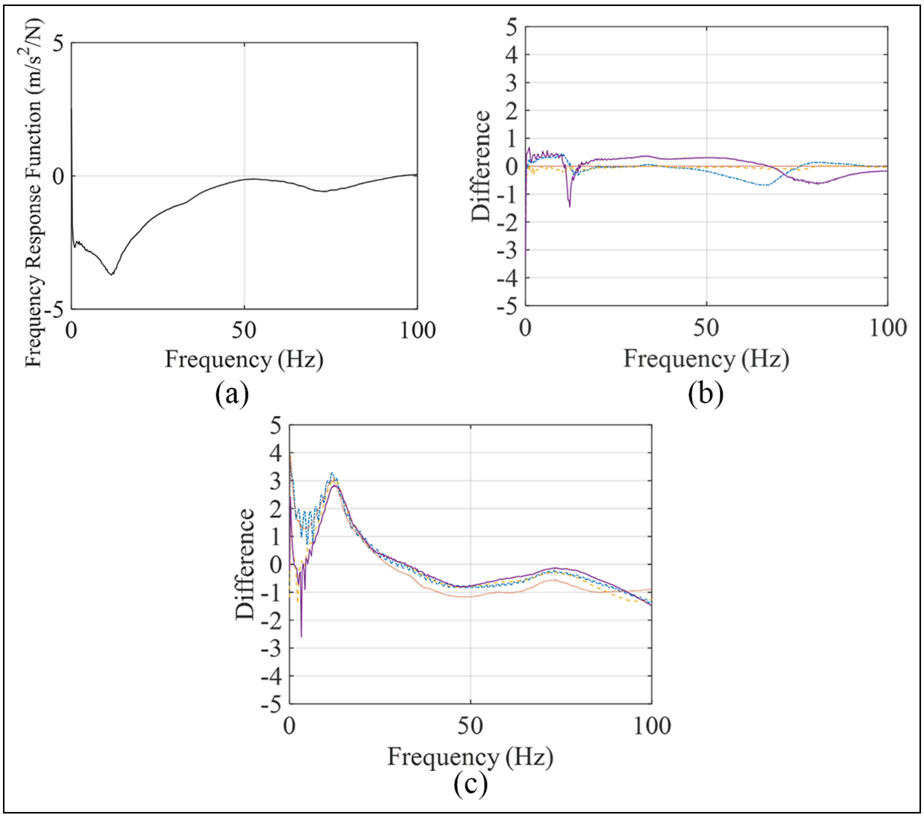

Figure 14. Animal bone: Plots showing differences between the reference signal without fractures: (a) a reference signal without fracture, (b) the four difference curves (the FRF signals without the fracture - the reference signal in (a)), and (c) the four difference curves (the FRF signals with fracture - the reference signal in (a)).

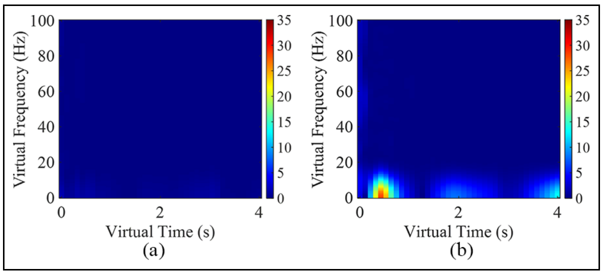

Figure 15. Virtual spectrogram: (a) spectrogram showing the differences in the responses without fracture and those without fracture and (b) spectrogram showing the differences in the responses with fracture and those without fracture.

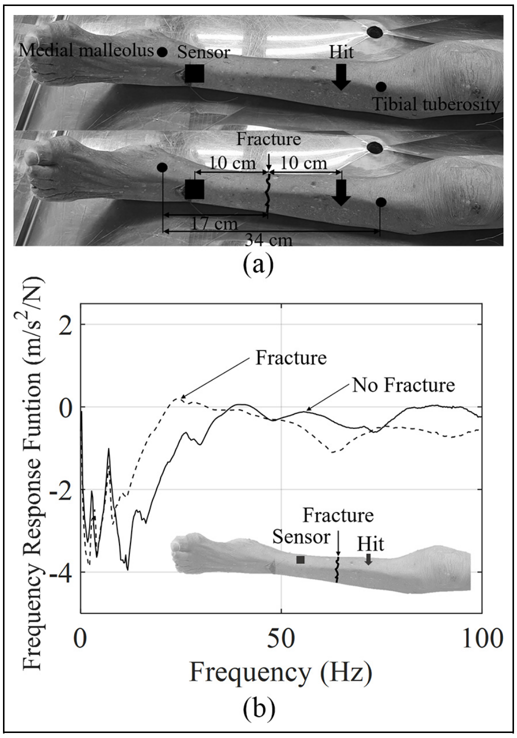

Figure 16. Cadaver fracture experiment: (a) legs with and without fracture and (b) the transverse vibration signals.

present study, owing to the difference between people, it is difficult to obtain so-called reference signals from the healthy bone. Thus, this research proposes to compare vibration signals considering the bilateral symmetry of humans. The low-frequency vibration of the counter part of the damaged bone is measured simultaneously considering the symmetricity of the human body, which is an advantage as it renders the diagnosis system more efficient and robust. In addition, the MAC-based criterion is proposed for the diagnosis. The frequency range and the criterion value should also be

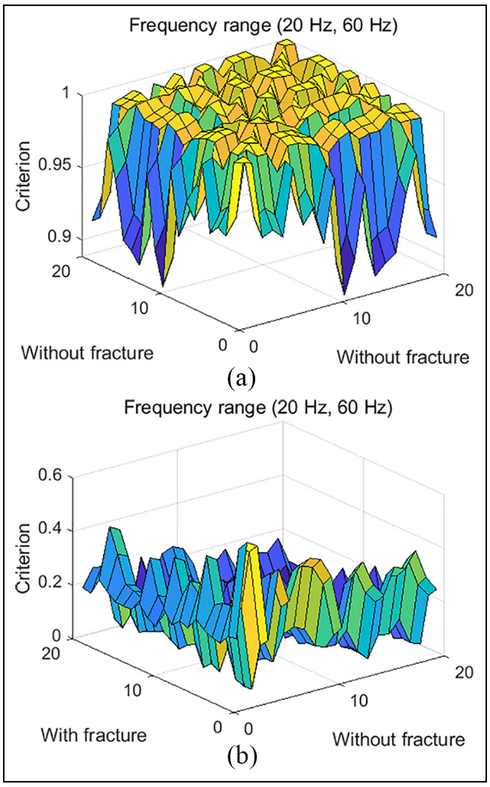

Figure 17. Illustration of MAC-based criterion (the *x* and *y* coordinates represents the number of experiments; here, 20 tests were conducted each for non-fractured and fractured specimens): (a) MAC values (fracture × no fracture) and (b) MAC values (fracture × no fracture).

determined. The results of our experiment demonstrate that transverse vibration signals below 100 Hz are appropriate for the characterization of the vibration signals. In the controlled and organized experiments with artificial and animal specimens, the lower limit of the frequency range can be set to 0 Hz. However, the systematic and controlled boundary conditions considering the bilateral symmetric condition cannot be set in experiments involving dead or living human bodies. Therefore, there should be caution when using frequency response data below about 20 Hz in diagnostic systems. The criterion value of the MAC-based criterion is around 0.5 depending on the frequency range of signals. The reference value of the MAC value is effective in determining whether an abnormality occurs. This reference value was tested on the frequency response obtained from artificial specimens, animal bones, and human bones. In summary, this smart diagnostic system can be expanded to a wide range of areas at low cost with excellent efficiency and excellent performance. For future research, the system can be extended to diagnose bones with fracture risk or known or suspected underlying bone diseases. The effect of the soft tissue (viscoelastic or viscoplastic material) and the different positions of actuators and sensors on transverse vibrations should be researched further. In addition, it is expected that a deep learning algorithm can be incorporated with this system.

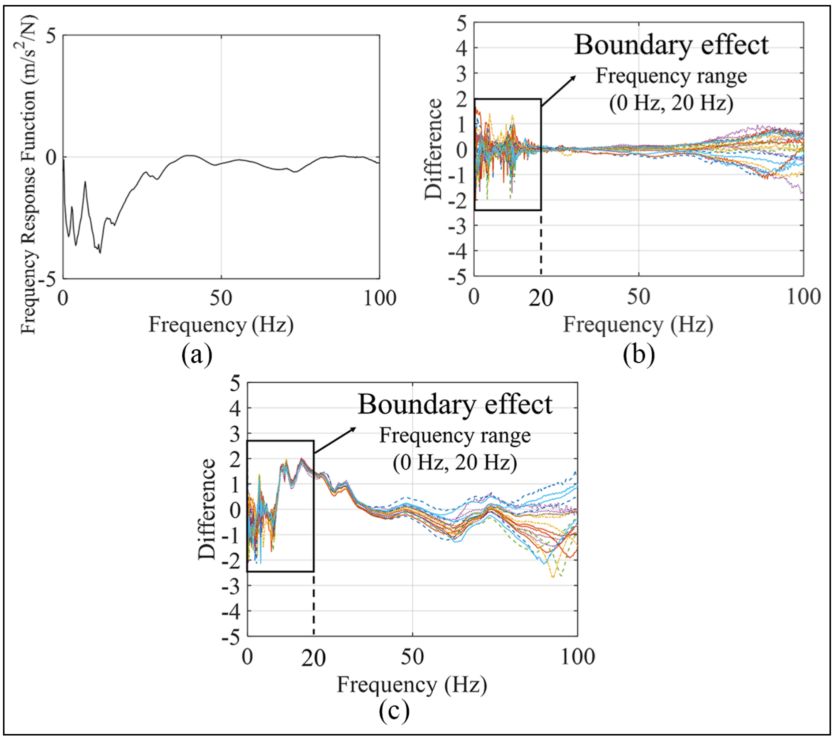

Figure 18. Cadaver experiment: Plots showing differences with the reference signal without fractures: (a) reference signal without fracture, (b) 20 difference curves (the FRF signals without the fracture – the reference signal in (a)), and (c) 20 difference curves (the FRF signals with fracture – the reference signal in (a)).

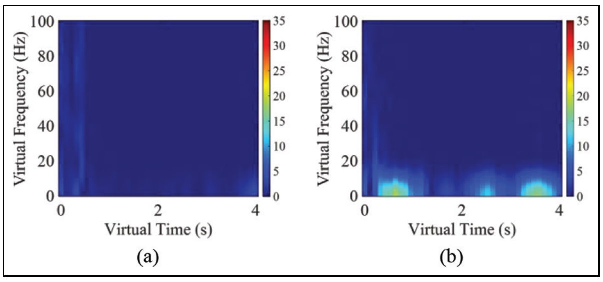

Figure 19. Virtual spectrogram with cadaver experiment: (a) a spectrogram with the difference between the responses without fracture and without fracture and (b) a spectrogram with the difference between the responses without fracture and with fracture.

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Declaration of conflicting interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: To follow the regulation of Republic of Korea, 2020, the cadaver experiment was conducted in the hospital of Hanyang University, Korea with the donated cadaver to College of Medicine of Hanyang University. As the cadaver was donated to College of Medicine, Hanyang University for the education and research, the regulations of IRB are not applied to the cadaver experiment at Republic of Korea, 2020.

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References

1. Hariz MI and Zrinzo L. *CT/MRI technology: Basic principles*. Berlin, Heidelberg: Springer, 2009.
2. Toney CM, Games KE, Winkelmann ZK, et al. Using tuning-fork tests in diagnosing fractures. *J Athl Train* 2016; 51(6): 498–499.
3. Ali R. *Bone vibration analysis as a novel screening tool for long bone fractures*. PhD Thesis, Sheffield Hallam University, 2019.
4. Dimililer K. Ibfds: intelligent bone fracture detection system. *Procedia Comput Sci* 2017; 120: 260–267.
5. Joutsen A, Hautalahti J, Jaatinen E, et al. A device for measuring sternal bone connectivity using vibration analysis techniques. *Proc IMechE, Part H: J Engineering in Medicine* 2020; 234(1): 81–90.
6. Mattei L, Di Puccio F and Marchetti S. Fracture healing monitoring by impact tests: single case study of a fractured tibia with external fixator. *IEEE J Transl Eng Health Med* 2019; 7: 1–6.
7. Razaghi H, Saatchi R, Offiah A, et al. Spectral analysis of bone low frequency vibration signals. In: *8th International symposium on communication systems, networks & digital signal processing (CSNDSP)*, Poznan, Poland, July 18–20, 2012, pp.1–5. New York, NY: IEEE.
8. Nokes L. The use of low-frequency vibration measurement in orthopaedics. *Proc IMechE, Part H: J Engineering in Medicine* 1999; 213(3): 271–290.
9. Varley P, Hession J, Creedon L, et al. Monitoring bone fracture using vibration analysis. 12th Annual Multidisciplinary Research Conference at Sligo General Hospital. November 2011.
10. Benirschke S, Mirels H, Jones D, et al. The use of resonant frequency measurements for the noninvasive assessment of mechanical stiffness of the healing tibia. *J Orthop Trauma* 1993; 7(1): 64–71.
11. Cunningham J, Kenwright J and Kershaw C. Biomechanical measurement of fracture healing. *J Med Eng Technol* 1990; 14(3): 92–101.
12. Kalmet PH, Sanduleanu S, Primakov S, et al. Deep learning in fracture detection: a narrative review. *Acta Orthop* 2020; 91(2): 215–220.
13. Yang AY, Cheng L, Shimaponda-Nawa M, et al. Long-bone fracture detection using artificial neural networks based on line features of x-ray images. In: *2019 IEEE symposium series on computational intelligence (SSCI)*, Xiamen, China, 6–9 December 2019, pp.2595–2602. New York, NY: IEEE.
14. Dodd SP, Cunningham JL, Miles AW, et al. Ultrasound transmission loss across transverse and oblique bone fractures: an in vitro study. *Ultrasound Med Biol* 2008; 34(3): 454–462.
15. Pastor M, Binda M and Harčarik T. Modal assurance criterion. *Procedia Eng* 2012; 48: 543–548.
16. MATLAB. Deep Learning Toolbox version 14.0 (R2020a). Natick, Masachusetts: The MathWorks Inc., 2020.