Noncontact optical sensor for bone fracture diagnostics

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Abstract: We present the first steps of a device suitable for detection of broken and cracked bones. The approach is based on temporal tracking of back reflected secondary speckle patterns generated when illuminating the limb with a laser and while applying periodic pressure stimulation via a loud speaker. Preliminary experiments are included showing the validity of the proposed device for detection of damaged bones.

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References and links

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1. Introduction

An adult human skeleton consists of 206 bones. The bones perform vital functions: storing different mineral salts, supporting soft tissues and various organs. The bones create the posture of the body and the ability to move. Bone cracks and fractures are caused due to different external forces. Broken bones are usually accompanied by pain due to the fact that pain nerves surround the bone and furthermore, the muscles that surround the fracture support the bone and might go into spasms. Due to these reasons quick and simple detection of bone fractures is significant [1].

The techniques available today for detection of fractures or bone defects are X-ray radiation, computed tomography, ultrasound, and magnetic resonance. The main technique used today for detection of fractures or bone defects is X-ray radiation [2]. This widespread method suffers from a number of disadvantages. First, there is a relationship between X-ray radiation and the risk of having cancer [3, 4], particularly in cases of pediatric patients [5, 6]. In addition, due to the risk of cancer, X-rays that directly target the womb are not recommended. Second, in the presence of certain medical conditions, even low doses of radiation raise the risk of radiation-induced meningioma [7, 8] and breast cancer [9–11].

Other techniques for bone fracture detection are computed tomography (CT) [12] and ultrasound (US). Computed Tomography [13, 14], which is ionizing radiation, also constitutes a significant risk of cancer, particularly in pediatric patients. Although ultrasound is not ionizing radiation, the presence of speckles and other artifacts impede image interpretation [15]. Magnetic resonance (MR) can also detect bone fractures [16, 17]; however, this method is very expensive. All the above mentioned techniques require complicated systems, which can be found mostly in hospitals and therefore are not very convenient for the patient.

In this paper we present a safe and simple method for diagnosing broken bones which is effective and affordable for the risk groups mentioned above. The limb is illuminated with an eye safe laser and the back reflected secondary speckle patterns [18] are analyzed with a camera. The use of such a concept was already demonstrated for non-contact biomedical...
monitoring including different biomedical parameters such as heart rate [19], blood pressure [20], remote estimation of alcohol in bloodstream [21], non-invasive monitoring of glucose concentration in blood [22, 23] and measurement of intraocular pressure. In this paper we adjust the concept and perform experimental validation of the speckle based sensing technology to analyze the responsivity of the measuring setup to pressure waves and vibrations that are applied via loudspeaker and from that to deduce the possibility of fractions or cracks in the bonds of the inspected organ.

2. Theoretical explanation

As previously explained the temporal movement of the bone or the skin surface causes temporary changes in the random speckle pattern [19]. In order to monitor the bone vibration, the correlation of each of the sequential images is measured. The relative movement of the stimulated bone was extracted by analyzing the change in the correlation peak position as shown in Fig. 1. The correlation is computed between each sequential image in the captured video sequence [23].

![Fig. 1. The temporal change in the position of the correlation peak (in pixels) versus time (the inset presents zoom of the temporal signal over 6 of its periods).](image)

The relative shift of the speckle pattern is proportional to [11]:

\[ \beta = \frac{4\pi \tan \alpha}{\lambda} = \frac{4\pi \alpha}{\lambda} \]

where \( \alpha \) is the time varying tilting angle of the illuminated surface as is shown in Fig. 2, \( \beta \) is proportional to the change in the spatial position of the speckle pattern due to the bone’s temporal movement, \( \lambda \) is the illumination wavelength, which in our case was 532 nm.

![Fig. 2. Schematic diagram of the system.](image)
By only checking the correlation peak position between adjacent frames, the result is expressed by integers. However, when using polynomial fit method, the position of the maximal value of the correlation peak is much smaller than a single pixel. The temporal movement of the bone is proportional to the change in the speckle pattern that is caused by the loudspeaker vibrations.

In order to detect a bone fracture we calculated the frequency response of the bone at the excitation frequencies (main peak) when vibrated due to the loudspeaker excitation. The frequency response is expressed as:

\[ X(k) = \sum_{j=1}^{N} x(j) \cdot e^{-j \pi k/N} \]  

(2)

where \( x(j) \) is a temporal vector of the change in the position of the correlation peak versus time, \( N \) is the number of frames that were captured during each sample and \( X(k) \) is the frequency response raw data. An example of frequency responses of broken and complete bone is shown in Fig. 3. The result is similar to a Bode’s diagram where the amplitude of the different vibration modes is measured in pixel’s shift of the correlation peak. One can see that the healthy-unbroken bone provides a vibration spectrum with peaks at 150 Hz (the excitation frequency) while the peaks of the broken one differs in amplitude (at 150 Hz). Note that there are parasites frequencies due to different external vibrations (e.g. electronic equipment, lighting of the laboratory etc). In fact, one can see in Fig. 3 that the change at frequency of 244 Hz is negligible with respect to the change at the tremor frequency.

The broken bone has a different response than a non-broken bone due to the following reasons: (1) the inner part of the bone is softer than the outer part of the bone. As it is shown in Refs [24–27], softer materials have the ability to better transmit vibrations. (2) When the bone is cracked or broken, a new edge is created at the broken bone spot. This new edge vibrates with higher amplitude than the complete part of the bone.

![Fig. 3. (a) Frequency response of complete bone. (b) Frequency response of broken bone. The excitation frequency during this experiment is 150 Hz.](image)

3. Experimental results

The constructed experimental setup (Fig. 4) consists of a laser (we used green laser at 532nm but an infra-red and eye-safe laser at 1550 nm can be used as well), loudspeaker and a camera.
Fig. 4. The optical configuration for remote measuring of bone fractures. The bone fracture is positioned under a laser illumination.

The loudspeaker was connected to a signal generator and it was located below (visible with difficulty in the picture) the inspected bone. The camera (Pixel Link PL-E531) was connected to a computer for the recording of the secondary speckle pattern reflected images from the bones at sampling rate of 700 frames per second (fps). The distance from the laser to the bone was approximately 5cm. The laser output power was approximately 5mW and five different excitation frequencies (50Hz, 100Hz, 150Hz, 200Hz and 250Hz) were examined (as it will be shown, these five excitation frequencies produced consistently good results with the proposed system, hence, these particular frequencies were used). The laser is CW and is collimated and focused. The beam size is approximately 5mm. The beam power density is 254.65 W/mm². Note that the power density of the sun is 1367 W/mm²; hence, the laser source of the proposed system is considered to be very safe to the human skin.

3.1 Stability test

The stability of the middle phalanx hand bone was checked, i.e. between the distal interphalangeal joint (DIP) to the proximal interphalangeal joint (PIP) as shown in Fig. 5(a). This test is important for two reasons: first, to ensure that the differences in the results are due to a fracture of the bone. The second is to show the ability of our device to monitor human bones and extract a profile as was extracted from chicken’s bones. During the test, one sample was tested 15 times where the excitation frequency was 150Hz (Fig. 5(b)). The finger was removed from the device after every sample. In Fig. 5(c) one can see that the highest deviation from the average is not more than 7.92% during the test.

Fig. 5. (a). The optical configuration for remote measuring of middle phalanx hands bone. The finger bone is positioned under a laser illumination. (b). Displacement of the correlation peak of the fingers bone. The excitation frequency during this experiment is 150 Hz. (c). Stability test of human bone, the difference in values from the average is displayed (in percentages).
3.2 Main test

In the second part of the experiment we examined a chicken’s femur bone frequency response (i.e. peak speckle displacement at the excitation frequency) when the bone vibrated at different frequencies (50 – 250 Hz). First, a piece of unbroken chicken's femur bone was illuminated, vibrated and finally the same bone was broken and the same experiment, under the same conditions was conducted again. The experiment was conducted on six different chickens’ femur bones. The frequency response of broken bone at the excitation frequency was examined with respect to the frequency response at the same frequency of identical complete bone (i.e. the second leg of the same chicken). Both broken and complete bones frequency responses were divided by the frequency response of the complete bone, hence, if the broken bone’s frequency response divided by the complete bone is bigger than 1, the optical measurement is compatible with the theory (i.e. in a case of optical result being higher than the complete bone, we diagnose the bone as broken bone).

Due to external noises, few of the result at different excitation frequencies were effected with low SNR (<1.5) which resulted with few unreliable results and so these were not included in the paper (i.e. only 25 samples were evaluated). As it is shown in Fig. 6 in 88% of the broken bones the frequency responses were above the detection threshold that we set. The meaning of this result is that only 12% of the results are missed.

In the third part of the experiment we illuminated a chicken domestic while the beam was aimed on one of the chicken’s bones (located within the illuminated tissue). After illuminating a broken bone we conducted the same experiment on a different reference piece of chicken while the bone of the chicken is unbroken. The conditions of this part were the same as the first one. In this part, the detection threshold is the frequency response of the reference piece of chicken. Different broken bones (which was also located within the illuminated tissue) frequency response result was normalized according to the reference piece. In order to evaluate the performance of our device in this experiment (Fig. 7) we performed 40 optical measurements on every sample. 90% of the samples were above the normalized
threshold (the threshold was set according to the normalized reference piece) as it is shown in
the following figures.

As one can see from the last results, the probability of true detection is 90%. Thus, the
proposed technique may be used as a new, simple, cheap and safe sensor with the ability to
diagnose bone fractures.

Fig. 7. (a). Optical samples of broken bone while we illuminated a piece of chicken compared
to a reference complete bone (red line). (b). A zoom-in of the optical samples of broken bone
while we illuminated a piece of chicken, compared to a complete reference bone (red line).

4. Conclusions

In this paper we have presented the usage of movement sensing technique based upon the
analysis of secondary speckle pattern in order to detect fractures in bones in a safer way. The
proposed concept involves a camera, a laser and a small loud speaker. The proposed
technique was experimentally validated on chicken bones.

The fracture test showed high prediction rate, 90% prediction of broken bones that was
located within the illuminated tissue compared to a whole piece of bone that was also located
within different reference illuminated tissue. This is the first step towards developing a small
and simple device which detects a bone fracture location by illuminating an injured bone
compare to complete one.

This technology could be used to diagnose a bone fracture within intact tissue in two
different ways: (1) by comparing the scans of the injured bone with a scan of an identical
bone in the same spot (2) scanning different spot of the same bone. Please note that the future
sensor will be very simple and extremely compact (approximately 3x3X1 mm) due to the fact
that the sensor consists of only a laser and a camera and it is attached to a digital signal
processor (DSP). Furthermore, the laser is very safe due to the fact that in the packaged form
its output optical power can be less than 0.5mW.