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Piezoelectric-film-based acoustic emission sensor array with thermoactuator for monitoring knee joint conditions

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ABSTRACT

This paper presents a novel piezoelectric lead zirconium titanate (PZT) thin film acoustic emission (AE) sensor array equipped with thermoresponsive polymer actuators that enhance its sensitivity for monitoring knee joint conditions. A hydrothermal PZT film was grown on a micromachined titanium-film four-beam array for use as an acoustic sensing material. The thickness of the grown film was 10 μm and its grain size was less than 1 μm. Moreover, it had a perovskite structure and demonstrated strong piezoelectric properties. A thermoresponsive polymer poly(N-isopropylacrylamide) (PNIPA) was formed on the beam array to electrically control the pressure on the sensing beam array and the underlying micropins. Such control was required for achieving an excellent couple for detecting a target, thereby increasing the sensitivity to AE signals. The fabricated PNIPA actuator was observed to generate more than 0.5% strain under a load six times its weight. Furthermore, the array configuration rendered the AE source detection more accurate compared with a regular single-detection-head sensor. The developed AE sensor was used for noninvasively examining the knee joint condition of a porcine leg when executing continuous back-and-forth motion. The result indicated that a joint under moderate extensive motion yielded higher AE signal amplitude and a wider bandwidth at major dominant frequencies compared with the joint before its extensive motion. An over-exercised joint with obvious cartilage degeneration yielded considerably high AE amplitude and a change in the pattern of dominant frequency peaks.

1. Introduction

The knee joint is a crucial joint structure in the human body because the movements enable people to accomplish numerous day-to-day tasks. Therefore, maintaining the knee joints under optimal conditions helps make life more colorful. However, many unpredictable factors trigger the destruction of or even damage the cartilage of the knee joint. Aging and over-exercise may also degenerate the cartilage [1,2]. Osteoarthritis is the most prevalent joint disease and aging is among its main risk factors [3]. Aging related cellular changes in articular cartilage consist of cell depletion due to different forms of cell death, impaired responses to extracellular stimuli, resulting in abnormal gene expression and cell [4]. Excessive exercises would compress the articular cartilage, which causes adverse effects by increasing the internal flow of water leading to the disruption of the matrix and susceptibility to degenerative changes [5]. Once the cartilage deteriorates considerably, the damaged articular surface and the reduced joint function causes aggravating pain, necessitating medical treatment. For example, symptoms found in persons with osteoarthritis include pain, temporary stiffness after inactivity, crepitus and swelling. These features are usually insidious in the beginning and are not associated with systemic disturbance. The common treatment prescribed for osteoarthritis is for symptomatic relief, to control the pain and improve joint function. Some of the therapeutics targets disease symptom such as nonsteroidal anti-inflammatory drugs, but find dominant side effects on the aging population. Intra-articular injections of corticosteroids and hyaluronic acid, which have demonstrated their safety and effectiveness, are frequently employed for symptom relief [6,7].

Clinical physicians examine joint conditions by using several commercially available noninvasive techniques such as X-ray, ultrasound, and magnetic resonance imaging [8,9]. These techniques provide visual data useful for evaluating the internal joint structure. However, the accessibility and cost of magnetic resonance imaging could pose restrictions for potential patients. Besides that, X-ray and ultrasound technicians need professional training to have a thorough understanding of how to operate

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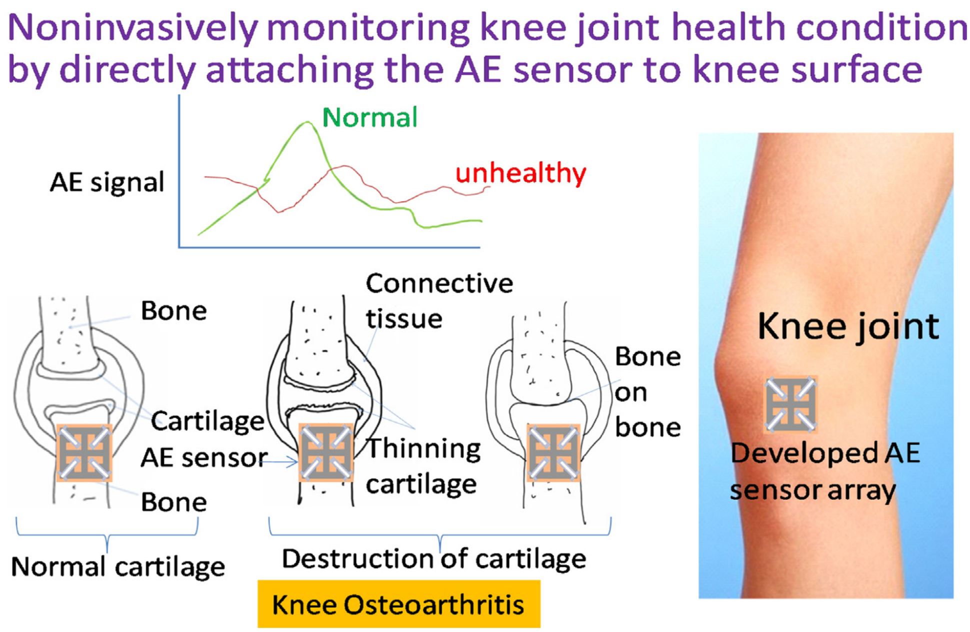

Fig. 1. Concept of the novel AE sensor array for monitoring the health condition of knee joint.

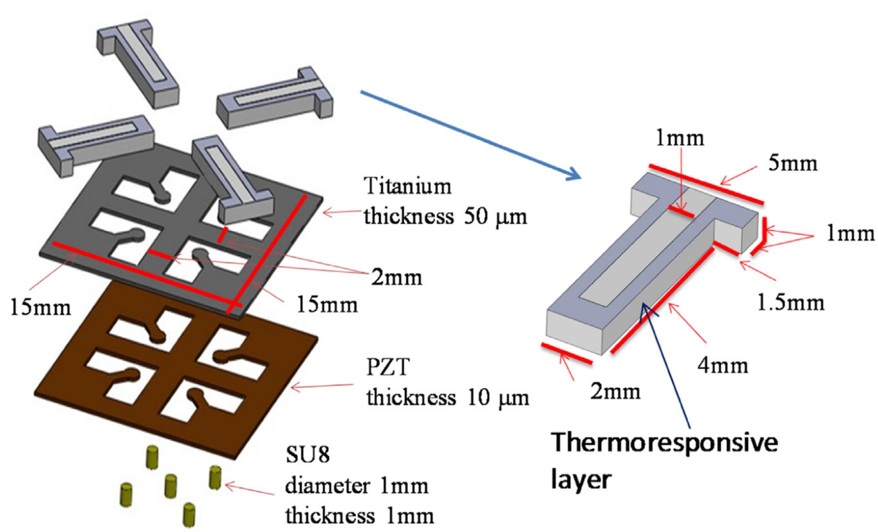

Fig. 2. Configuration of proposed AE sensor array with exploded-view drawing.

their medical imaging equipment. The training and establishment of experience usually require some time and effort. In addition, these techniques typically provide only static information. A cost-effective online noninvasive detection technique can certainly be beneficial to both doctors and patients. Such a technique can provide insight into the joint condition and clues to the causes of joint degeneration.

Distinctive sound patterns are produced during joint movement. A normal knee with adequately lubricated cartilage surfaces undergoes smooth movements, whereas an unhealthy knee covered by a rough and poorly lubricated cartilage surface shows uneven movements, producing a different pattern of acoustic signals [10]. In recent years, several dynamic sensing techniques for examining joint health condition have been reported. Phonoarthrography, which is one of the earliest techniques, is based on auscultation and involves using conventional microphones to record the sound produced by a moving knee joint in the audible frequency range of 20 Hz–20 kHz [11]. Subsequently, vibroarthrography was introduced to evaluate the status of a moving joint. Researchers have used small accelerometers with a frequency response lower than 1 kHz to obtain dynamic signals from a knee joint and to diagnose the associated knee symptoms [12,13]; they have typically attached the accelerometers to the knee joint. In recent years, acoustic emission (AE), which provides considerably high frequency information, has drawn attention to the possibility of online monitoring of the condition of joints [14–16].

In general, AEs is pressure waves generated because of a transient release of energy when a material of interest is subjected to mechanical, thermal, or chemical changes that cause irreversible deformation or changes to the atomic arrangement [17]. Typically, an AE can be considered a high-frequency sound generated by a structure under loading or interaction between two surfaces. The magnitude and characteristics of the generated AE are dependent on the source characteristics [18]. Because the detected frequency is beyond the audible range (>20 kHz), the AE signals carry short wavelength information. Therefore, these signals offer the advan-

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