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An implantable ultrasonic sensor for continuous monitoring of wound rehabilitation

Ye Tian[1], Yueying Yang[1], Hanchuan Tang[1], Jianfeng Zang[1,2]
[1] School of Integrated Circuits and Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan, China. 430074
[2] The State Intelligent Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan, China. 430074

Corresponding Author's e-mail address: dr.ye.tian@gmail.com

Summary:

Implantable devices for continuous, wireless monitoring of tissue rehabilitation are crucial for personalized health. Traditional electronic sensors, though small and flexible, struggle with biomechanical matching, biodegradability, biocompatibility, and wireless monitoring. Here, we introduce an electronics-free implantable strain sensor using ultrasonic metagel for continuous monitoring of wound rehabilitation. Tested on porcine tendon and wounded tissue in live pigs, the metagel monitors tissue rehabilitation continuously and wirelessly.

Keywords: Implantable sensor, strain sensor, flexible sensor, acoustic metamaterials, ultrasound

Title

AN IMPLANTABLE ULTRASONIC SENSOR FOR CONTINUOUS MONITORING OF WOUND REHABILITATION

Background, Motivation an Objective

The development of the metagel strain sensor is rooted in the growing need for advanced monitoring solutions in personalized healthcare, particularly for wound rehabilitation[1]. Traditional implantable electronic sensors, despite being small and flexible, face significant challenges in terms of biomechanical compatibility, biodegradability, biocompatibility, and effective wireless monitoring[2,3]. These limitations can hinder their long-term use and integration with biological tissues. Motivated by these challenges, the metagel strain sensor in this work provide a more effective, biocompatible, and biodegradable alternative for continuous and wireless monitoring of tissue rehabilitation.

Description of the New Method or System

In this work, we present an ultrasonic implantable metagel strain sensor for continuous and wireless monitoring of internal tissue rehabilitation. By utilizing a hydrogel-based 2D phononic crystal structure, the metagel sensor can seamlessly integrate with soft tissues and wirelessly transmit strain data through ultrasonic bandgap shifts, offering a promising solution for real-time monitoring and rehabilitation of wounds.

Results

In this article, an ultrasonic strain sensor, composed of air cells in soft hydrogels, is designed for continuous monitoring of internal tissue rehabilitation. The ultrasonic metagel sensor stands out due to its all-hydrogel design, eliminating the need for rigid materials like semiconductor chips or metal components. As a result, the metagel sensor offers outstanding softness, biocompatibility, and biodegradability, along with the long communication distance, all of which are essential for implantable sensors in clinical applications.

The schematic of the metagel implant, which consists of periodic air columns embedded in soft hydrogels, is shown in **Fig. 1**. The wireless monitoring system uses an ultrasonic probe placed on the skin's surface. Deformation of the metagel causes a shift in the ultrasonic bandgap, detectable by the external ultrasonic probe. This probe emits ultrasounds towards the internal metagel implant and captures the returning echoes. By analyzing the spectral characteristics of these echoes, the sensor can detect internal tissue strains. The phononic crystal design, formed by the periodic structure, has an acoustic bandgap defined by its dimensional parameters. As the metagel stretches, the acoustic bandgap shifts to a higher frequency, causing a corresponding shift (Δf) in the peak frequency of the echoes.

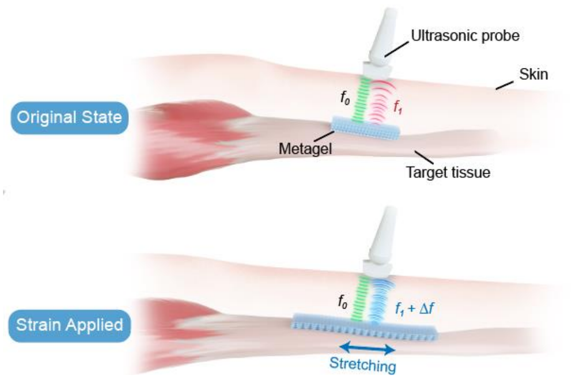

Fig. 1. Mechanism of the metagel strain sensor.

To characterize the frequency shift of the metagel sensor more clearly, the movement of the peak frequency was measured in a typical stretch-release cycle within 20% strain as shown in **Fig. 2**. The shift of the echo's peak frequency during the stretching process exhibited similar behavior to that during the release process, indicating dependable performance in 20% strain.

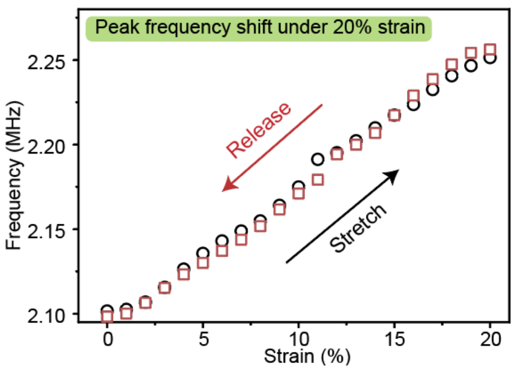

Fig. 2. Strain sensing ability of the metagel sensor.

To verify the strain sensing ability of the metagel sensor in vivo, the metagel was implanted on the broken tendon to monitor the tendon stretching in live pigs. The metagel sensor on the broken tendon shows a larger frequency shift than normal tendon under the same bending process (**Fig. 3**). Therefore, the metagel sensor can be used to monitor tendon dehiscence in clinical applications. After the ruptured tendon re-grows and connects, the frequency shift of the metagel sensor was reduced under the bending process of the pig's foot. Thus, the wound healing progress can be observed through long-term and continuous monitoring of tendon strains using the metagel sensor.

Similar to the monitoring of the broken tendon, the metagel sensor can also be used on the monitoring of the subcutaneous wound. Two subcutaneous wounds were created by tissue excision on the back of a pig, then a normal metagel and a metagel with growth factors were respectively attached on each wound to achieve two different wound healing rates, as shown in **Fig. 4**. According to amplitudes of the frequency shift generated by breathing, we can monitor the wound recovery process. The faster the wound tissue grows, the quicker the decrease in frequency shift generated by breathing.

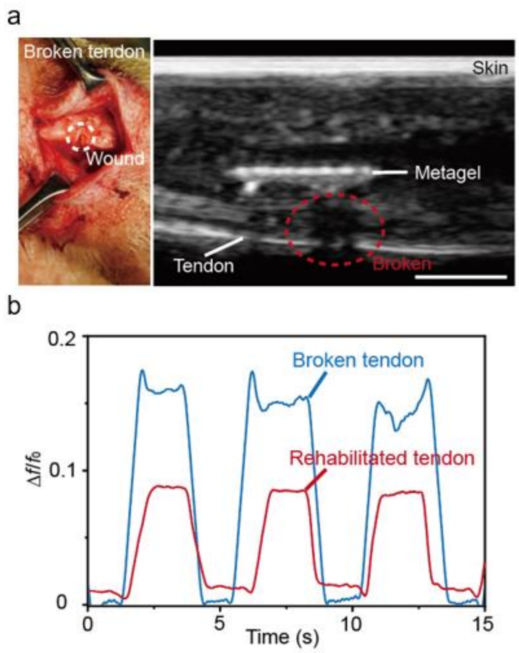

Fig. 3. Monitoring of the broken tendon's rehabilitation on day 1 (blue line) and day 7 (red line) post-implantation.

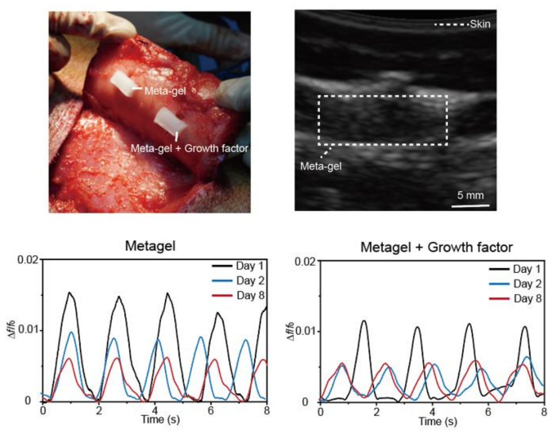

Fig. 4. Monitoring of the subcutaneous wound rehabilitation using the normal metagel (left) and metagel loaded with growth factors (right).

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