SMART monitoring and treatment of fracture healing: Piezoelectric transducers and stepper motor actuators

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https://doi.org/10.5937/vojtehg72-49720

FIELD: electrical engineering, mechanical engineering, telecommunications, biomedical engineering
ARTICLE TYPE: review paper

Abstract:

Introduction/purpose: SMART orthopedic systems use fixators with remote monitoring, processing, and communication capabilities to leverage healing progression data for personalized, real-time monitoring of a healing process. The fixators incorporate small and compact piezoelectric sensors that generate electrical signals upon the application of force to the piezoelectric diaphragm. This enables doctors to remotely guide fixation devices using indirectly and remotely controlled stepper motors known for their precision and accuracy. Reliability of stepper motors makes them a viable alternative for the mechanical tools traditionally used by doctors for fixator extension.

Methods: This study focuses on the evaluation of sensor-based technology in orthopedic applications. The paper presents a theoretical framework for the application of SMART devices in the bone fracture healing process. It delves into the structure and functionality of piezoelectric transducers, *offering a comprehensive insight into this technology and various engineering aspects of SMART systems.*

Results: The implementation of SMART systems has significantly enhanced doctor-patient communication. This improvement is facilitated through a dual-phase process involving gathering, processing, and transmitting the data wirelessly from the patient's (sensor) interface to the doctor who uses specialized software for data analysis and wireless transmission to the stepper motor actuator. Subsequently, the data is forwarded to the decoder at the motor site, where a motor controller generates the control signal for the stepper motor driver.

Conclusion: SMART implants can provide doctors with quantitative data that can be used in directing a rehabilitation plan. The sensor-based technology offers insights into the stress induced by the callus formation enabling bidirectional communication between the doctor and the patient. The stepper motor is a tool that aids in personalized treatment from the distance.

Key words: SMART implant, piezoelectric sensor, fracture healing, stepper motor.

Introduction

Traditional technologies used to monitor fracture healing mostly rely on imaging techniques such as radiography, computed tomography (CT) scans, magnetic resonance imaging (MRI), and ultrasound, which are subjective, involve radiation, and expensive (Bizzoca et al, 2023; Nicholson et al, 2021; Coneicao et al, 2023). Efforts in improving bone healing were firstly focused on measuring fracture stiffness based on external fixation (Pelham et al, 2017). However, internal fixation is now the preferred method for treating lower limb fractures due to the drawbacks associated with external fixation, such as patient discomfort, prolonged recovery time, and infection risks (Friis et al, 2017; Sellei et al, 2015; Antic et al, 2023a). To monitor interfragmentary movement, implanted devices with internal power sources and instrumented bone plates are commonly used (Ernst et al, 2020). Recent advancements in long bone healing involve innovative methodologies using both external and internal fixators, introducing new remote detection, processing, and communication systems. The development of multifunctional Self-Monitoring Analysis and Reporting Technology (SMART) implants incorporating various sensing, actuation, processing, and power systems, represents an emerging trend in this field (Soares dos Santos & Bernardo, 2022). SMART implants have the potential to provide personalized, real-time monitoring of the healing process even after the patient has been discharged from the hospital

(Antic et al, 2023a). In their study, Borchani et al. (2016) describe sensor-based monitoring devices equipped with an internal power source and an instrumented bone plate for monitoring interfragmentary movement. At the site of a bone fracture, these devices gather data on the patient's activity. The collected raw data is subjected to statistical processing, storage, and/or transmission. A significant challenge arises from the fact that sensor packages are too large to be integrated into small orthopedic components such as fracture fixation plates, microcontroller units, and power sources (Sun, R. et al, 2018). The design based on piezoelectric sensors eliminates the need for an external power source, which simplifies the construction and implementation of fixators.

Piezoelectric materials have the ability to generate electrical signals without external stimulation. The distortion of the internal dipole caused by applied mechanical force generates surface charge, resulting in the generation of electrical signals (Tandon et al, 2018). When a force is applied to the piezoelectric diaphragm, an electric charge is generated across the crystal faces. The output is measured as voltage that is directly proportional to applied pressure (Antic et al, 2023b). Consequently, piezoelectric sensors can function as self-powered, battery-free sensors with inherent mechano-electric energy capabilities. These sensors enable the accurate capture of various information from the environment. Parameters such as fracture stiffness, void geometry deformation, bending moment, and other relevant factors can be monitored to facilitate the healing process of a fractured bone (Claes & Cunningham, 2009; Antic et al, 2023a).

The SMART sensor system must be designed to utilize data related to healing progression in order to provide doctors with information about fracture healing, which necessitates that it incorporates acquisition and processing systems capable of detecting electrical changes in various stages of fracture healing including not only sensors but also analogue-to-digital (A/D) and digital-to-analog (D/A) converters, data processing and storage devices, as well as communication system for data transmission (Coneicao et al, 2023).

The use of remote data monitoring and acquisition of the fracture activity profile is considered a distinguishing feature of the SMART sensor-based concept compared to passive techniques for in vivo monitoring (Green & Gianchandani, 2009). Through remote monitoring, doctors can guide fixation devices from a distance, if necessary, to align bone fragments and facilitate the formation of new callus tissue. This can be achieved using indirectly and remotely controlled devices such as miniaturized stepper motors known for their precise and accurate movements, fine resolution, low noise, high torque capabilities, reliability, and durability. Stepper motors translate electrical pulses into precise mechanical movements, while the controller keeps track of the number of steps taken. Their excellent dynamic characteristics enable quick starts and stops, making stepper motors widely used in medical applications for controlling critical aspects of patient care, such as infusion pumps, systolic pumps, respiratory devices, dialysis machines, CT scanners, MRI machines, surgical instruments, and medical robots (Kumar, 2021). The reliability of stepper motors makes them suitable for replacing mechanical tools used by doctors to extend fixators.

This article highlights the use of SMART implant systems consisting of the piezoelectric sensor and data processing, storage, and transmission units. It is shown that communication between the sensor transmitter and the receiver at the doctor's site can enhance the personalized healing process. Furthermore, the use of stepper motors is discussed, demonstrating their ability to adjust external fixators without the doctor's physical presence.

SMART orthopedic implant systems

Bones form a solid structure known as the skeleton which provides the support and protection of internal organs (Andrew, 2024). The bones contain one of the hardest tissues that make up the human body representing a suitable medium for biomechanical analysis, the results of which could be applied in the treatment of bone fractures. The healing process of bone fractures is governed by the achieved mechanical stability and maintenance of broken bone fragments in a specific position to ensure smoot progression of the healing process (Sheen et al, 2023). Minimal distance between bone fragments as well as minimal movement between them is essential until a solid new bone tissue (callus) is formed. There are two basic methods of bone fracture fixation. The internal method involves placing the entire fixation implant beneath the skin (Friis et al, 2017; Sellei et al, 2015). The external fixator entails the use of pins and needles inserted into the bone, passing through skin and soft tissues and attached externally to a fixator frame (Pelham et al, 2017). External fixators are commonly used for open fractures and where the postoperative corrections may be necessary.

SMART implants

Orthopedic implants that are considered SMART are typically small and compact electrically powered devices used for the purpose of diagnosis, monitoring, and treatment (Ledet et al, 2018). These implants have the capability to measure pressure, force, strain, displacement, proximity, and temperature, in addition to other physical stimuli that can assist in the process of fracture fixation (Ledet et al, 2018). Fracture fixation can be achieved through the use of fracture plates, intramedullary rods and external fixators. Loads are transmitted through both the bone and the fixator when a bone is loaded. During the acute postoperative period, the forces are transmitted solely to the fixator since the fracture cannot withstand loads. As the bone callus forms and the fracture heals, the bone gradually begins to bear some load, thereby reducing the force on the fixator. The SMART implant system typically comprises a sensor chip, a reader unit, and a battery (Antic et al, 2023b). Electrochemical monitoring is made possible through on-chip microelectrodes. The sensor readout unit is built upon an application specific integrated circuit. The sensor reading and bi-directional data transmission between the implant and the interface is enabled by a microcontroler integrated into the reader unit. All the components of the system are designed to operate on low power.

Implant materials

Despite significant advancement in the technology of SMART implants, there are still several obstacles that need to be addressed such as implant failure mechanisms, toxicity, infection, corrosion of metal implants, design, and effectiveness of implants used in fracture fixation (Shayesteh Moghaddam et al, 2016).

Metals have unique and valuable characteristics in terms of their extensive surface areas and biological properties which encompass biocompatible loading and heat transfer. Due to the high mechanical stress resistance and fracture toughness of cobalt, iron, nickel and titanium, these were the pioneering materials used for implants, and continue to be extensively used (Binyamin et al, 2006; Shekhawat et al, 2021). Additionally, metal alloys like cobalt, magnesium, stainless steel, and titanium alloys are frequently used for implants to attain specific properties such as corrosion resistance, elasticity, and strength (Poinem et al, 2012; Shekhawat et al, 2021). Stainless steel is the most frequently used in metallic implants due to its affordability and ease of production. However, its high stiffness compared to bone can result in bone resorption from stress shielding. Stainless steel may also trigger an inflammatory response as its oxide becomes conductive (Jacobs et al, 1998). On the other hand, cobalt-based alloys surpass stainless steel in terms of biocompatibility, corrosion resistance and strength, albeit at higher manufacturing costs

(Brogini et al, 2021; Solanke et al, 2021). Titanium and its alloys are characterized by low density, excellent biocompatibility, and an oxide layer for bone progenitor cells attachment (Xu et al, 2020; Anene et al, 2021). Nickel-titanium, commonly used in orthodontic wires and vascular stents, has the lowest elastic modulus among biocompatible metals having bone-like biomechanical properties (Taheri Andani et al, 2014). Titanium-based materials, although very expensive, are reserved for patients with hypersensitivity reactions to cobalt-based or stainless-steel alloys. Magnesium, with a density slightly lower than that of the bone, can serve as an osteo-conductive and biodegradable implant material in load-bearing applications. However, controlling its high corrosion rate is crucial to ensure its suitability for biomedical applications (Findik, 2020).

In decades, synthetic materials have progressed from biocompatible substances to bioactive materials. By adjusting the composition, polymeric compounds can mimic the structure of different tissues while retaining their mechanical characteristics. Among synthetic materials, polyurethane (PE) is recognized as one of the most versatile substances suitable for orthopedic implants (Francis, 2021). The increasing use of polymers is driven by their costs-effectiveness and adaptability. The key benefits of using PE include low friction resistance, resistance to abrasion and impact, good biocompatibility, favorable tensile properties, tensile strength and flexural rigidity (Jefferies et al, 2021). However, its drawbacks include the generation of heat and the release of methyl methacrylate monomer during the in-situ polymerization process (Rohani Shirvan et al, 2021; Allizond et al, 2022). With the rise in the life expectancy and surgical procedures, there is a growing demand for implants that are highly reliable and resistant to fractures. Bio-ceramics are a type of wear-resistant materials with high fracture toughness. They are categorized into three groups: bioinert materials that do not react with the living tissue and are non-toxic, showcasing exceptional stability and mechanical properties, but with high manufacturing costs (zirconia, alumina); biodegradable substances that are absorbed by the body; and bioactive materials capable of forming bioactive glass (Piconi, 2017).

SMART orthopedic fixation

Movements around the fractured area and the natural muscle tension tend to dislocate the fracture. When external fixation is utilized, these movements can strain the pins and the frame of the external fixator, causing micromovements and micro-deformations. This effect is particularly noticeable in cases of external fixation involving weight-bearing bones of the lower extremities. The forces from lower extremity movements, muscle tension, and the body's weight during standing and walking all contribute to the issue. As the callus hardens, more of the load is gradually transferred through the bone and less through the external fixator, resulting in a reduction of micromovements and micro-deformations. SMART fixators have the capability to provide objective data that can assist doctors in guiding patient rehabilitation strategies at various stages of treatment. Monitoring loads during weight-bearing is typically used to indicate the process of fracture consolidation and healing (Borchani et al, 2016). SMART internal fixators using bone plates have shown promising results in comparison to other surgical methods. Studies describe postoperative fracture monitoring by electrical impedance spectroscopy (Lin et al, 2019), and the measurement of physical stimuli achieved through application-specific technology of the implant (Ledet et al, 2018). In addition, the integration of intelligent features into orthopedic implants containing wireless transceivers and microsensors has significantly improved implant capabilities. However, certain challenges such as ensuring the reliability of wireless links, downsizing implants, providing adequate power supply, high measurement accuracy, affordability, and low complication rates, still need to be addressed (Naghdi et al, 2023). The main advantages, challenges, and future perspectives of the SMART concept are listed in Table 1.

Table 1 – Advantages, disadvantages, and expectations of the SMART concept

Advantages	**Disadvantages**	**Future perspectives**
Data analytics Data integration Information exchange Interoperability IoT Remote monitoring and controlling Target audience Wearable sensor technologies/Portability Wireless/wired transmission	Accuracy Battery life Complexity Discomfort High costs Reliability of wireless links Security Stability	Affordability Artificial intelligence Biomedical sensing Cost effectiveness Decentralized medicine Mobile health Personalized health care User friendly Time effectiveness

Sensor-based diagnostic

The sensor system serves as an active device that not only possesses the capability to make automatic decisions but also has the ability to control actuators based on those decisions. The system comprises several key components, including excitation control, amplifiers, converters, and analog filters. These components work together to convert mechanical stimuli into electrical signals determined by responses to mechanical strain (Kausar, 2022). Among various types of stretchable strain sensors, capacitive and resistive sensors have received significant attention among researchers. Capacitive strain sensors are constructed by placing an insulating foil between two stretchable electrodes (Amjadi et al, 2016). When subjected to strain, the capacitance of these sensors increases due to geometric changes in the capacitive region, independent of the resistance value of the electrodes. Resistive sensors are designed in the stretchable format. When stretched or compressed, the electrical resistance of these sensors changes in response to the applied mechanical stress.

In terms of sensors system diagnostics, there are two types of measurements: external and internal. Both types incorporate sensing and active devices that facilitate real-time monitoring of bone fracture healing. Pelham et al. (2017) discuss external measurements which involve indirect measurements of fracture stiffness as an indicator of bone union, as well as the monitoring of the mechanical response of external fixation devices. Furthermore, Chiurazzi et al. (2020) explore the functions of capacitive sensors in relation to relative rotation and translation of external fixator pins used to determine the status of bone healing. Borchani et al. (2016) discuss an internal approach to long-term measurement that includes a microprocessor.

Devices most commonly used for measuring strain in SMART sensor orthopedic devices are strain gauges. Strain gauges are metallic transducers used for accurate measurements of forces, loads, weight, or tension. The resistance in a strain gauge varies in direct proportion to the level of strain. A strain gauge consists of a small wire or a metallic foil arranged in a grid pattern, which is bonded to a thin carrier attached to a bone and undergoes a linear change in its electrical resistance when the bone experiences strain (Button et al, 2013). Strain gauges have the advantage of being able to be directly attached to the object being measured, streamlining the measurement procedure. They are particularly suitable for extended periods of measurements making them ideal for long-term monitoring. Furthermore, the simplified process of extracting relevant information from the gathered data facilitates data analysis. Additionally, strain gauges exhibit a high capability to adjust for variations in temperature, enhancing their overall utility. Piezoelectric force sensors or force transducers used in SMART orthopedic systems are typically installed directly at the measurement point allowing for immediate readiness of conducted measurements. They are designed for precise measurements, strategically positioned and calibrated to take into account factors such as the structure geometry, the material modulus of elasticity, and the mechanical stress (Sirohi & Chopra, 2000). These transducers capture electrical charge through the application of force on a piezoelectric crystal which is then converted into a voltage signal using the charge amplifier. Due to atomic-level shifts that cause charge effects, the deformation is extremely small. This allows for the creation of highly rigid structures with high natural frequencies. Such characteristics are particularly advantageous for capturing fast and high-frequency measurements. The disadvantages encompass the high volatility of electric charge captured by the crystal and its tendency to decrease over time, along with the vulnerability of piezoelectric transducers to temperature fluctuation.

Piezoelectric transducers

Piezoelectric transducers generate an electrical charge in response to applied mechanical stress. These transducers are commonly used in systems that measure various physical stimuli, including force, pressure, strain, and temperature (Jacobs et al, 1998). The transducer circuit comprises internal resistance, an inductor connected to generate inductance due to the inertia of the sensor, and capacitance that is inversely proportional to the elasticity of the sensor material. Unlike other transducers, piezoelectric transducers do not require an external voltage source as they directly generate an electrical signal based on the applied strain. Consequently, these transductors function as piezoelectric sensors. Moreover, transducers can also convert electrical signals into mechanical energy or physical movement, thereby operating as piezoelectric actuators. Hence, a piezoelectric transducer can be regarded as a combination of a piezoelectric sensor and an actuator, and its specific design determines whether it performs both roles or only one of them. Piezoelectric transducers are compact, robust, and shock-resistive. These attributes, combined with their high frequency response, make them suitable for record players, accelerometers, electronic watches, microphones, seat bells, kitchen stoves, infertility treatment, printers, smartphones, automatic doors, and a wide range of applications. The small size of piezoelectric transducers allows for easy integration into almost any device, as they can provide precise measurements across a broad spectrum. This characteristic makes them highly adaptable and often requires minimal adjustments to fit into existing designs. Piezoelectric transducers boast flexible design options and requirements, as they can be shaped into various forms to meet specific needs. A notable feature of piezoelectric transducers is their high-frequency response and accuracy. A rapid response to pressure changes makes them ideal for applications that demand precision down to fraction of a millisecond (particularly suitable for medical devices).

It is worth mentioning that piezoelectricity has also been discovered in bones, suggesting its involvement in important signaling mechanisms related to tissue function (Aherwar et al, 2016). Recently, piezoelectric sensors became promising candidates for integration into Internet of Things (IoT) technologies (Brogini et al, 2021). However, the transmission and reception of data over wireless channels can be extremely vulnerable to malicious attacks since wireless communication involves the transfer of significant amounts of personal information which individuals generally prefer to keep confidential (Li & Li, 2022).

Piezoelectric transductor: functions and structure

The piezoelectric transductor used for monitoring bone healing transforms the force associated with the size and structure of a newly formed callus. The application of mechanical deformation to a polarized crystal of the piezoelectric diaphragm induces electrical charge generation, i.e. a sensor generates an electrical signal in response to compression or tension (transduction) (Kausar, 2022). The key attributes of piezoelectric transductors include their flexibility and lightweight nature, dynamic and frequency range, high resistance to mechanical stress and impact, and availability in a variety of thicknesses and sizes. In sensor applications, the flat part of the frequency response (the relationship between the force input and the voltage output versus the frequency) is commonly used. The useful region for a sensor is usually between the high-pass cutoff and the resonant peak (Figure 1). Low frequencies are filtered out by the leakage resistance while the high frequencies resonate (Bansal, 2012).

The output voltage generated by a piezoelectric sensor can also serve as a power supply for additional functionalities like wireless communication (O'Connor & Kiourti, 2017). By using a piezoelectric material in the construction of the sensor, the resulting output voltage can be effectively measured to identify the strain. Consequently, the analysis of the output voltage enables motion detection. It is important to note that sensors with different designs have distinct characteristics such as durability, hysteresis, linearity, sensibility, and stretchability (Kim et al, 2022).

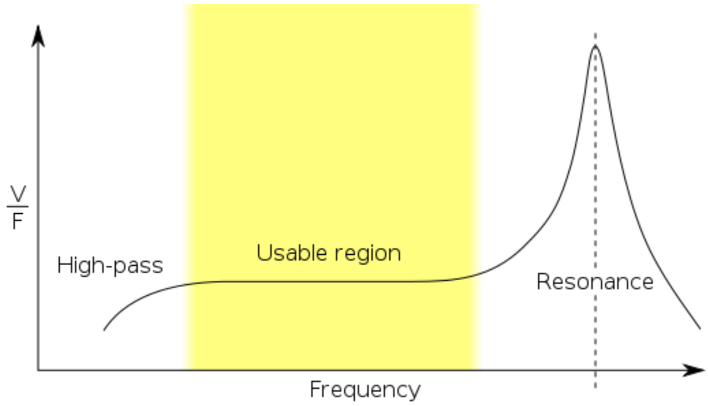

Figure 1 – Piezoelectric sensor frequency response

Data acquisition and processing

The increasing need for customized, non-hospitalized medical care has led to the growth of telemedicine, a system that uses information and communication technologies to share health data and deliver healthcare services. This innovative approach enables two-way communication between patients and doctors. When coupled with telemonitoring, telemedicine can serve a s a valuable diagnostic tool by remotely tracking patients' physiological data through sensors, microprocessors, and wireless data transmission for real-time data processing (Aguirre et al, 2016). The biomedical data related to the broken limb is a crucial element of personalized treatment, involving sensing, acquiring, processing, and interpreting bio-signals to gather essential information for doctors. The process of data acquisition (DAQ) involves the conversion of analogue signals into the digital format, ensuring both accuracy and speed to enable computer processing. This process occurs in three stages: sensing, signal processing and analysis. The sensing stage involves converting physical characteristics into electrical signals, while the signal processing stage transforms these signals into a format that can be understood by software, embedded platforms, and computer devices. Finally, the analysis stage extracts valuable features to aid in decision making (Sun, G. et al, 2018). The key components of a data acquisition system include: transducers which transform the measured quantity into an electrical signal that is proportional to the input; devices that adjust the sensor signal to the appropriate level for analogue-to-digital (AD) conversion (such as amplifiers, converters, and filters); an anti-aliasing filter that eliminates high-frequency signals that may lead to inaccurate conversions; and various other units with different levels of complexity (Taylor, 1997). The block diagram of a DAQ system is given in Figure 2.

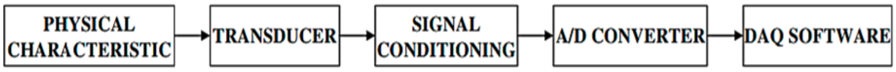

Figure 2 – Data acquisition and processing

The initial step in the data collection process involves identifying physical phenomena or characteristics that should be measured. Regardless of specific characteristic being measured, it must first be converted into the format that a DAQ system can handle. The conversion process is carried out by transducers. Piezoelectric crystal transducers convert applied force into electrical charge. The charge is then measured and converted into digital signals. The electrical signals obtained from the sensors may contain noise or other interference and need modification. The signals might also be weak to a point where the data acquisition system cannot measure them. Hence a signal conditioner is used to optimize the signals. It separates the noise from the real signal and utilizes an amplification circuit for strengthening weak signals. The A/D converter plays a crucial role in the DAQ system by transforming the data obtained from the surroundings into distinct levels that can be understood by a processor. A higher number of bits in an A/D converter results in an increased number of discrete levels available for encoding an analog signal, thereby enhancing resolution of the A/D converter. The execution of the DAQ software can be carried out by a microprocessor unit (MPU) which is capable of executing signal condition tasks specific to the process. The sensor can operate in a “report by exception” mode, where it transmits data only if there is a change in the measured variable. Additionally, the sensor may incorporate self-diagnostics, enabling the immediate detection of any developing drift in the outputs of its sensor elements. The data processing encompasses the transmission and reception of information through both wired and wireless channels. It is important to highlight that data processing, particularly when carried out wirelessly, is highly vulnerable to malicious attacks.

Telemedicine and communication protocols

The healthcare sector is currently experiencing a notable shift due to the progress in technologies, like the IoT, biosensing, non-invasive sensing, contactless sensing, artificial intelligence (AI), mobile applications, and cloud computing (Sun, G. et al, 2018). This has led to a series of challenges in the acquisition, monitoring, processing, and sharing of patients' data highlighting the necessity for healthcare solutions that are flexible, personalized, and easy to use in order to address growing demands.

Telemedicine refers to the application of electronics information and communication technologies for the provision and enhancement of health services in cases where there is physical distance between the patient and the doctor (Atmojo et al, 2020). In contrast to telehealth that covers remote clinical and non-clinical services, telemedicine mostly focuses on remote clinical services provided by doctors (Kruse et al, 2017). It also provides convenience to both patients and doctors by eliminating the need for in-person visit to seek medical advice or treatment. Telemedicine is proved to be a cost-effective alternative when compared to the traditional approach to medical services and care. Telemedicine operations necessitate a thorough understanding of telecommunication technologies, networking and medical device technology. One of the most captivating advancements in telemedicine pertains to the capability of incorporating devices for self-monitoring or supervision by doctors (Cram, 2004). Telemedicine predominantly relies on desktop/laptop computers equipped with specialized software and corresponding devices, offering the advantage of secure data storage, processing, and transferring. Based on the mode of operation, telemedicine can be divided into an asynchronous (store-and-forward), synchronous (real-time), and remote monitoring. The patient is provided with health care through the telecommunication system (Thomas, 2023). The communication in telemedicine relay on the following standards and protocols for wired and wireless communication: Bluetooth (IEEE 802.15.1), Wi-Fi/WLAN (IEEE 802.11), WiMAX/Broadband Wireless Access (BWA) (IEEE 802.16), ZigBee (IEEE 802.15.4), Real-Time Protocol (RTP), Real-Time Transport Control Protocol (RTCP), Transmission Control Protocol/Internet Protocol (TCP/IP), and User Datagram Protocol (UDP).

Stepper motor actuator: a tool for enhancing extension mechanisms

Stepper motor actuators (SMA) are electromechanical devices that transform electrical pulses into distinct rotation movement referred to as "steps" (Harb & Zaher, 2004). They consist of a stepper motor, a mechanical transmission mechanism, and a control system. The stepper motor is a synchronous electric motor that moves in discrete steps and has a capability to achieve accurate control over position and speed without requiring feedback systems. Stepper motors can be divided into permanent magnet stepper motors (PMSM), variable reluctance stepper motors (VRSM), and hybrid stepper motors (HSM). PMSM make use of permanent magnets on the rotor and EM stator poles. PMSM have favorable torque-to-size ratios (frequently used in cost-effective applications). VRSM have a soft iron rotor without magnets and generate torque based on the magnetic reluctance principle. They have the ability to achieve high step rates, and are frequently used in high-speed applications. HSM combine characteristics of both PMSM and VRSM. HSM have a multi-toothed rotor equipped with permanent magnets, resulting in higher torque, improved resolution, and smoother operation compared to PMSM or VRSM. The mechanical transmission mechanism in a SMA converts the motor rotary motion into linear or other motion types using lead screws, ball screws, belts, and pulleys. The control system manages the stepper motor operation by sending electrical pulses to its windings, determining its speed, direction, and step size.

The SMA used in medical devices are required to possess several characteristics, including small size, accuracy, smooth motion, quiet operation, reliability, and quality. In medical applications, limited space is often a critical factor, making smaller SMA highly desirable (Cheng & Scattareggia, 2011). To choose the most suitable SMA for a specific application, it is crucial to take into account various factors which include load, speed and acceleration requirements, resolution and precision needs, operating environment, and costs. Firstly, one needs to determine the force or torque necessary to move, lift or hold the load. This information will assist in selecting the appropriate motor size and transmission mechanism. Secondly, the desired speed and acceleration should be considered, because they will have an impact on the control system selection. Next, the required positioning resolution and accuracy should be evaluated. This will aid in choosing the motor type and the step angle.

The SMA can serve as a tool to facilitate a gradual bone lengthening procedure, enabling the bone to slowly increase in length. The fixator can be adjusted at a rate of approximately 1mm per day, until the bone has fully hardened and calcified (ICLL, 2024). The objective of the SMA is to carry out a distinct rotation of the stepper motor's movement as directed by the physician and managed remotely. It should be noted that the doctor has the ability to accelerate or decelerate the rate of distraction if necessary. The SMART orthopedic external implant system shown in Figure 3 is designed to use the SMA properties to eliminate the necessity for mechanical tools during implant extension. This system comprises a piezoelectric sensor (PES), a stepper motor (SM), and a data acquisition and processing module (DAPM).

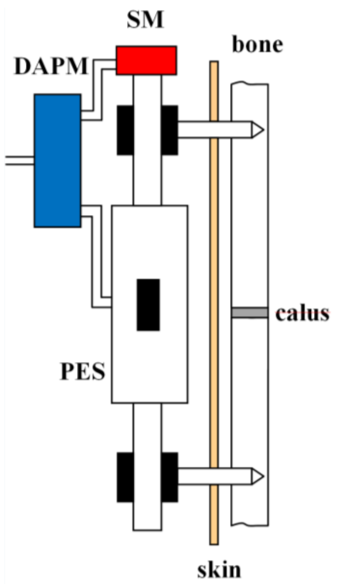

Figure 3 – SMART implant containing PES, SM, and DAPM

Effective doctor-patient communication is achieved through a hardware-software platform by providing doctors to access to bone healing data and allowing them to control the movements of broken bone parts through the stepper motor placed on the fixator. The communication process follows a two-way protocol where both parties activate processing devices and communication channels. Due to the limitations of the wired control system in controlling stepper motors over a long distance, wireless technologies are commonly used for this purpose (Sowjanya et al, 2018).

The first stage involves gathering data from the sensor, processing the data, and transmitting it wirelessly (see Figure 2). Upon reception at the doctor's location, the data is processed and encoded in the proper format. The doctor then examines the data, makes decisions, and initiates the software for processing, formatting, and wireless transmission to control SMA. Upon reaching the motor site, the data is received by the receiver unit, forwarded to the decoder, and a motor controller is used to generate the control signal for the stepper motor driver (Abas & Bakar, 2016). Various microcontroller chips with Wi-Fi interfaces can be used for the stepper motor control, including Espressif System ESP 8266, Microchip PIC16F series, Texas Instrument Stellaris, and Arduino Mega.

Conclusion

SMART orthopedic implants are devices used to measure physical stimuli during the process of fracture fixation. The implants use on-chip microelectrodes and a sensor readout unit built on an application specific integrated circuit for electrochemical monitoring. When external fixation is used, the movements of the broken bone can strain the pins and the frame of the fixator. Various factors such as extremity movements and muscle tension contribute to this issue. As the callus hardens, a load is gradually transferred from the fixator to the bone, resulting in a reduction of micromovements. SMART devices provide objective data that can assist doctors in guiding rehabilitation strategies of patients at different stages of treatment. The sensor system is an active device capable of making automatic decisions and controlling actuators based on those decisions. The SMA can be used to aid in a bone healing procedure. Effective communication between doctors and patients is achieved through a hardware-software platform, which grants that doctors asses to bone healing data and enables them to control the movements of broken bone parts through a stepper motor. The doctor reviews the sensor data, make decisions based on the information and triggers the SMA for stepper motor activation.

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SMART, Monitorización y tratamiento de la curación de fracturas: transductores piezoeléctricos y actuadores de motor paso a paso

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CAMPO: ingeniería eléctrica, ingeniería mecánica, telecomunicaciones, ingeniería biomédica
TIPO DE ARTÍCULO: artículo de revisión

Resumen:

Introducción/objetivo: Los sistemas ortopédicos SMART utilizan fijadores con capacidades de comunicación, procesamiento y monitoreo remoto para aprovechar los datos de progresión de la curación para un monitoreo personalizado en tiempo real de un proceso de curación. Los fijadores incorporan sensores piezoeléctricos pequeños y compactos que generan señales eléctricas al aplicar fuerza al diafragma piezoeléctrico. Esto permite a los médicos guiar de forma remota los dispositivos de fijación utilizando motores paso a paso controlados indirectamente y de forma remota, conocidos por su precisión y exactitud. La confiabilidad de los motores paso a paso los convierte en una alternativa viable a las herramientas mecánicas utilizadas tradicionalmente por los médicos para la extensión del fijador.

Métodos: Este estudio se centra en la evaluación de la tecnología basada en sensores en aplicaciones ortopédicas. El artículo presenta un marco teórico para la aplicación de dispositivos SMART en el proceso de curación de fracturas óseas. Profundiza en la estructura y funcionalidad de los transductores piezoeléctricos ofreciendo una visión integral de esta tecnología y diversos aspectos de ingeniería de los sistemas SMART.

Resultados: La implementación de sistemas SMART ha mejorado significativamente la comunicación médico-paciente. Esta mejora se facilita mediante un proceso de dos fases que implica recopilar, procesar y transmitir los datos de forma inalámbrica desde la interfaz (sensor) del paciente al médico, que utiliza software especializado para el análisis de datos y la transmisión inalámbrica al actuador del motor paso a paso. Posteriormente, los datos se envían al decodificador en el sitio del motor, donde un controlador del motor genera la señal de control para el controlador del motor paso a paso.

Conclusión: Los implantes SMART pueden proporcionar a los médicos datos cuantitativos que pueden utilizarse para dirigir un plan de rehabilitación. La tecnología basada en sensores ofrece información sobre el estrés inducido por la formación de callos, lo que permite la comunicación bidireccional entre el médico y el paciente. El motor paso a paso es una herramienta que ayuda al trato personalizado a distancia.

Palabras claves: implante SMART, sensor piezoeléctrico, curación de fracturas, motor paso a paso.

УМНЫЙ мониторинг и заживление переломов: пьезоэлектрические преобразователи и актуаторы шаговых двигателей

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РУБРИКА ГРНТИ: 34.57.00 Биоинженерия
ВИД СТАТЬИ: обзорная статья

Резюме:

Введение/цель: В умных ортопедических системах используются фиксаторы с возможностью дистанционного мониторинга, обработки и связи для использования данных о ходе лечения с целью персонализированного мониторинга процесса заживления в реальном времени. В состав фиксаторов входят небольшие и компактные пьезоэлектрические датчики, которые генерируют электрические сигналы при приложении усилия к пьезоэлектрической диафрагме. Это позволяет врачам дистанционно управлять фиксирующими устройствами, используя шаговые двигатели с косвенным и дистанционно управляемым приводом, отличающимися своей точностью. Надежность шаговых двигателей делает их надежной альтернативой механическим инструментам, традиционно используемым врачами для удлинения фиксаторов.

Методы: Данное исследование посвящено оценке сенсорных технологий в ортопедических приложениях. В данной статье представлены теоретические основы применения УМНЫХ устройств в процессе заживления переломов костей. Также обсуждается структура и функциональность пьезоэлектрических преобразователей и дается всестороннее представление о данной технологии и различных инженерных аспектах УМНЫХ систем.

Результаты: Внедрение УМНЫХ систем значительно улучшило коммуникацию врачей с пациентами. Такому прогрессу способствует процесс, включающий сбор, обработку и беспроводную передачу данных от интерфейса больного (датчика) врачу, который использует специальное программное *обеспечение для анализа данных и беспроводной передачи актуатору шагового двигателя. После чего данные передаются в декодер двигателя, где контроллер двигателя генерирует контрольный сигнал для драйвера двигателя.*

Выводы: Умные имплантаты могут предоставить врачам количественные данные, которые можно использовать для составления плана реабилитации. Сенсорная технология дает представление о стрессе, вызванном образованием мозолей, обеспечивая двустороннюю связь между врачом и пациентом. Шаговый двигатель служит инструментом в персонализированном дистанционном лечении.

Ключевые слова: УМНЫЙ имплантат, пьезоэлектрический датчик, перелом кости, шаговый двигатель.

Смарт третман у зарастању прелома: пиезоелектрични претварачи и актуатори степ мотора

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ОБЛАСТ: електротехника, машинство, телекомуникације, биоинжењеринг
КАТЕГОРИЈА (ТИП) ЧЛАНКА: прегледни рад

Сажетак:

Увод/циљ: Смарт ортопедски системи користе фиксаторе са могућношћу даљинског праћења, обраде и комуникације како би искористили податке о напредовању лечења за персонализовано праћење процеса зарастања у реалном времену. Фиксатори садрже мале и компактне пиезоелектричне сензоре који генеришу електричне сигнале при примени силе на пиезоелектричну дијафрагму. То омогућава лекарима да даљински воде уређаје за фиксирање са удаљености користећи индиректно и даљински контролисане степ (корачне) моторе познате по прецизности и тачности. Њихова поузданост чини их одрживом алтернативом за механичке алате које лекари традиционално користе за продужавање фиксатора.

Методе: Ова студија се фокусира на евалуацију технологије засноване на сензорима у ортопедским апликацијама. У њој је *представљен теоријски оквир за примену смарт уређаја у процесу зарастања прелома костију. Разматра се и структура и функционалност пиезоелектричних претварача и нуди свеобухватан увид у ову технологију и различите инжењерске аспекте смарт система.*

Резултати: Имплементацијом смарт система значајно је побољшана комуникација између лекара и пацијента. То је олакшано кроз процес који обухвата прикупљање, обраду и бежични пренос података од пацијентовог (сензорског) интерфејса до лекара, који користи специјализовани софтвер за анализу података и бежични пренос до актуатора степ мотора. Након тога подаци се прослеђују декодеру на локацији мотора, где контролер мотора генерише контролни сигнал за драјвер мотора.

Закључак: Смарт имплантати пружају лекарима квантитативне податке који се могу користити у усмеравању плана рехабилитације. Технологија заснована на сензорима нуди увид у стрес изазван формирањем калуса, омогућавајући двосмерну комуникацију између лекара и пацијента. Степ мотор служи као алат који помаже у персонализованом третману са удаљености.

Кључне речи: смарт имплантат, пиезоелектрични сензор, фрактура кости, степ мотор.

Paper received on: 08.12.2023.
Manuscript corrections submitted on: 07.06.2024.
Paper accepted for publishing on: 08.06.2024.