Indian Journal of Orthopaedics (2023) 57:1196–1202
https://doi.org/10.1007/s43465-023-00933-3

REVIEW ARTICLE

Sensor Technology in Fracture Healing

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Received: 14 March 2023 / Accepted: 8 June 2023 / Published online: 23 June 2023

Abstract

Introduction SMART sensor technology may provide the solution to bridge the gap between the current radiographic determination of fracture healing and clinical assessment. The displacement and rigidity between the fracture ends can be accurately measured using strain gauges. Progressively increasing stiffness is a sign of fracture consolidation which can be monitored using sensors. The design of standard orthopaedic implants can remain the same and needs no major modifications as the sensor can be mounted onto the implant without occupying much space. Data regarding various fracture morphologies and their strain levels throughout the fracture healing process may help develop AI algorithms that can subsequently be used to optimise implant design/materials.

Materials and Methods The literature search was performed in PubMed, PubMed Central, Scopus, and Web of Science databases for reviewing and evaluating the published scientific data regarding sensor technology in fracture healing.

Results and Interpretation SMART sensor technology comes with a variety of uses such as determining fracture healing progress, predicting early implant failure, and determining fractures liable for non-union to exemplify a few. The main limitations are that it is still in its inception and needs extensive refinement before it becomes widely and routinely used in clinical practice. Nevertheless, with continuous advances in microprocessor technology, research designs, and additive manufacturing, the utilisation and application of SMART implants in the field of trauma and orthopaedic surgery are constantly growing.

Conclusion Mass production of such SMART implants will reduce overall production costs and see its use in routine clinical practice in the future and is likely to make a significant contribution in the next industrial revolution termed ‘Industry 5.0’ which aims at personalised patient-specific implants and devices. SMART sensor technology may, therefore, herald a new era in the field of orthopaedic trauma.

Keywords Sensor · Technology · Fracture · Callus

Introduction

Most orthopaedic surgeons determine the progress of fracture healing clinically based on mobility and tenderness at the fracture site and using radiographic evidence of calcification of the callus. This conventional technique is sub-optimal because the reported incidence of delayed and non-union of fractures is as high as 38% in some studies and is unable to determine impending implant failure [1]. Thus, there is a need to develop diagnostic modalities with high sensitivity that allow the surgeon to offer early intervention to the patient thereby reducing their financial burden and hardships. Smart sensor technology may, therefore, provide the solution to bridge this gap.

IoT (Internet of Things) represents the next generation of technology in medicine and includes technologies such as broadband internet, micro-electrical machine systems

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(MEMS), and new wireless communication (NFC, Bluetooth, and WIFI) [2]. In the field of orthopaedics, this has led to the development of SMART (Self-Monitoring Analysis and Reporting Technology) devices, which mainly assist doctors in measuring biomechanical quantities in the body, such as temperature, torque, force, and moments. They are typically utilised in the form of external sensors or implanted devices within the body that can gather data from the environment and wirelessly transfer it without the usage of assisted powering systems. These gadgets aid doctors and clinicians in patient rehabilitation monitoring, predicting early implant failures, and creating implants with improved biomechanical qualities [3, 4].

SMART Sensors

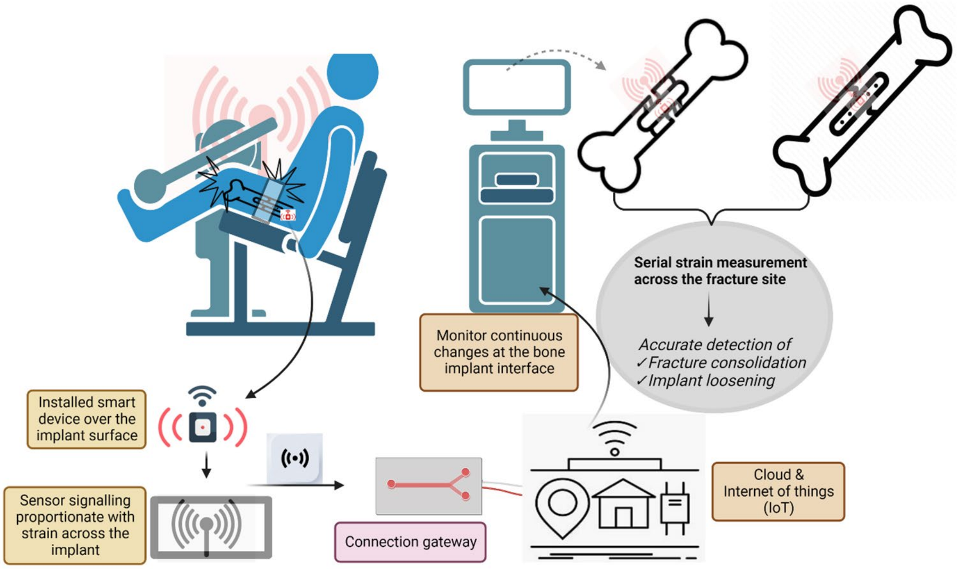
In the field of trauma, fracture healing is mainly dependent on the stress and strain levels around the surrounding tissue such as bone and cartilage. Immediately after fracture fixation using an implant, the load across the fracture site is taken up by the implant. However, as fracture healing progresses, the fracture callus gradually takes up the load, which reduces the strain transmitted across the implant. Hence, serial strain measurement across the fracture site after surgery can serve as a guide to fracture healing. This is the principle of the SMART sensor used in fracture healing and quantified fracture stiffness has been shown to demonstrate fracture healing up to 2.5 weeks before radiographic evidence [5, 6].

Conventional imaging modalities such as radiographs, CAT scans, bone scans and MRIs remain extremely subjective and are unable to monitor continuous changes at the bone–implant interface. To overcome these shortcomings, multiple sensors based on various strategies, such as inertial sensors (accelerometers and piezo-electric), ultrasonic sensors, inductive proximity sensing sensors, piezo-floating gate sensing and capacitive sensing, and the recently developed cosurface capacitive technology have been designed to offer accurate detection of bone healing progress and early implant loosening.

With development of multiple sensors based on varied strategies such as inertial sensors (accelerometers and piezo-electric) [7], ultrasonic sensors [8], inductive proximity sensing sensors [9], piezo-floating-gate sensing with capacitive sensing [10, 11], and the more recently developed cosurface capacitive technology [12]; bone healing progress and early implant loosening can be accurately detected. The schematic representation of smart sensors in fracture healing is depicted in Fig. 1.

External Fixators: In order to temporarily stabilise the bone, external fixators are medical devices with a semi-rigid metal frame and percutaneous pins. The displacement and rigidity at the fracture site can be measured easily, albeit temporarily, by instrumenting external fixation systems using strain gauges. For the purpose of keeping track of the condition of bone fractures as they heal, numerous techniques have been devised. These techniques include electromagnetic radiation, electrical impedance, and mechanical vibration. Extracorporeal mechanical excitation, extracorporeal electric current, extracorporeal mechanical load, and extracorporeal electromagnetic field are among the five techniques that have been specifically identified for external fixation systems [13]. These techniques were tested in vitro and in vivo by Mattei et al. to evaluate fracture healing by identifying changes in bone-callus stiffness. They applied a low-magnitude mechanical stress using an instrumented micro-hammer, and they employed extracorporeal accelerometers

Fig. 1 Schematic representation of smart sensors in fracture healing



to record mechanical vibrations. Resonant frequencies increased as the callus healing progressed; with greater increases being seen when the callus changed from a soft to a firm consistency. These technologies have the potential to be used instead of radiography to evaluate fracture healing, but their clinical application still has to be simplified and these techniques are particularly helpful only in the initial weeks of recovery since their efficacy declines as healing proceeds [14, 15]. Progressively increasing stiffness is a sign of fracture consolidation which can be monitored using sensors and strain levels of 15 N-m/degree for tibial fractures and 20 N-m/degree for femoral fractures are defined parameters to permit fixator removal [5]. Researchers have looked at other procedures to enhance the functional performance of external fixation, including vibrometric and impedance monitoring. The suggested techniques and technologies do, however, have certain drawbacks, such as limited specificity, an inability to monitor target areas, and the requirement for extracorporeal excitations. Patient-dependent performances are made possible using fixator pins to transmit input signals and collect output signals, but location-dependent sensitivity during callus development is a problem for impedance-based systems. The instrumented fixator created by Ernst et al. has the potential for continuous monitoring, but successful treatments call for building implantable instruments with more advanced circuitry and mechanisms for individualised monitoring [16]. Hardware and software solutions for bone-implant callus monitoring through HiFi connection have recently been developed [17].

Intramedullary nail: Brown et al. first described the use of multi-channel telemetry in their study on a battery-powered nail-plate system [18]. Schneider et al., in their study showed the different forces acting on a femur fracture managed using interlocking femur nails using telemetry sensors that wirelessly relayed data regarding strain transmission. They described the design of the nail with bending stiffness comparable to standard nails used in clinical practice despite being able to incorporate the telemetry relay circuit which is sealed off from body fluids. They showed that fracture consolidation reduces implant loads by up to 50% and highlighted the importance of muscular tone in fracture healing [19].

Plates: Mechanical vibration, electrical impedance, electric charge, electromagnetic radiation, and mechanical displacement have all been proposed to track the states of bone fracture [13]. Electric impedance is the approach for monitoring fracture healing that has received the most attention among the several technologies created for osteosynthesis plate systems. The difficulty to give high specificity for fracture healing states and the requirement for extracorporeal excitations are limitations [20]. These sensing devices guarantee efficient monitoring, including quantitative analysis, during all phases of the fracture healing process. The self-weight can be utilised for extracorporeal mechanical excitation, even though some technologies demand it. Capacitive bioreactance sensing systems may be made to work non-invasively without extracorporeal electric powering, in addition to being able to achieve high resolution and high sensitivity [11, 21, 22]. A wireless, biocompatible, micro electron mechanical system (BioMEMS) that uses a multi-sensor-implant construct with an external excitation/receiving apparatus (Fig) that can be mounted onto conventional plating systems is a highly effective device that wirelessly transmits strain data from the fracture site [23, 24].

Spine: Instrumented implants have made it possible to quantify spinal forces in vivo since the 1970s. Instrumented spine fixation devices, strain gauges on the lamina, and vertebral body replacement are all examples of current technology. In vivo tests have demonstrated that substantial vertebral body loads, ranging from 100 N when laying down to over 700 N when lifting weights or working out against resistance, are present during the first postoperative month [25]. Sensors are embedded in the lamina of vertebrae to detect spinal fusion following surgery. Serial measurements after surgery showed that strain over the fusion rod and strain over the bone were inversely proportional and bone strain increased gradually and plateaued once fusion was achieved [26]. Intracorporeal sensors have been utilised to quantify intradiscal pressures, but longer term monitoring of human intervertebral body forces is still a work in progress [25, 27, 28].

Infection: MEMS-based sensors in implants can be used to monitor bacterial biofilm before its formation using parameters such as O_2 concentration, pH, specific ion balance, and temperature [29]. Using commercially pure titanium (cpTi) substrates, cathodic voltage-controlled electrical stimulation (CVCES) has also been shown to lessen orthopaedic infections linked to methicillin-resistant *Staphylococcus aureus* (MRSA). According to in vitro and in vivo testing, CVCES at −1.8 V for 1 h significantly reduced the number of MRSA colony-forming units (CFUs) on the cpTi and surrounding solution, as well as on bone tissue and the cpTi implant. The stimulation did not cause any histological changes in the host tissue [30].

Strategies of Sensor Technology in Fracture Healing

The design of standard orthopaedic implants need not change as the sensor can be mounted onto existing designs without occupying much space. The main strategies that can be developed in order to progress sensor technology include the detection of the stability along bone-implant interface, the transfer of implant-clinician data, the therapeutic actuation to promote stable bone-implant constructs, and the self-powering of the electronics and instruments.

Therapeutic actuation can be accomplished by delivering biophysical stimuli in the form of mechanical stimulation via piezo-electric stimulators, which, while effective, were associated with the weakening of the implant-bone interface [31–33]. Ultrasound which is already a proven modality in fracture healing when administered via extracorporeal stimulation has also been tried and incorporated into implant systems but efficacy remains uncertain [8, 34].

Bioresorbable electrostimulation devices that are self-powered have also been described to not only monitor but also accelerate fracture healing using a triboelectric nanogenerator via electrical impulses [35]. Biomagnetic stimulation which has osteogenic, osteoconductive and osteoinductive capacity has also been harnessed in the form of a small-sized quasi-cosurface technique that delivers a customised magnetic field stimuli to peri-implant target locations in order to assure the delivery of efficient magnetic flux densities while needing (up to 50-fold) reduced electric current transfer [36, 37].

Moreover, methicillin-resistant *Staphylococcus aureus* (MRSA) colony-forming units might be dramatically decreased using a cathodic voltage-controlled electrical stimulator which is the main pathogen encountered in orthopaedic implants which may also aid in prolonged survival of the smart implant [30].

The self-powering ability remains the next major challenge with sensor technology as long-term use of these devices need electric generators which deliver high performance to facilitate the tasks such as actuation, processing and transfer. Routine use of batteries to power these sensors has failed to deliver the necessary power requirements as standalone technologies and hence there is a need for a self-powered system with low power consumption, low maintenance and self-adaptability [3]. The proposed area that is currently being explored is triboelectric and piezo-electric technology to scavenge motion across the joints of the body to harvest energy [38, 39]. These piezo-electric harvesters have shown promising early results in terms of power generation and storage, however, their long-term safety profile remains questionable [40, 41]. A series of wireless, battery-free, telemetry-free passive resonator-based sensors with no electrical connections has been described. These small and convenient sensors can be constructed in a variety of sizes to match the implant and are able to monitor factors such as force, temperature, pressure, and pH. These have, however, only been simulated in vitro environments so far, but holds enormous potential for smart implant technology in the future [42–45]. Few recent studies have proposed the use of magnetic levitation technology in electromagnetic harvesters in which self-adaptability is achieved by altering generator length with respect to human joint motion [46, 47].

Once strain levels needed for normal fracture healing across different bones and fractures are mapped out, AI can be used to create algorithms depending upon fracture characteristics that help the clinician track patient progress and determine the appropriate time for weight bearing post-surgery and also determine fractures going in for non-union thereby allowing early surgical intervention. They can also be used to determine increasing strain levels across the implant suggestive of implant fatigue, allowing surgeons to take the necessary precautions.

Limitations

Apart from the apparent cost factor, further high-quality evidence is required to establish the safety and efficacy of smart sensors in humans because the majority of the research being done at the moment is focussed on animal studies.

Sterility of the sensor implant continues to remain an issue since adequate sterility at recommended temperatures cannot be achieved due to temperature-sensitive electronic components. Thus, this technology is still in its inception and needs extensive refinement of design and compatibility before it becomes widely and routinely available for clinical use.

Future Directives

Sensor placement in the orthopaedic instrument can be used conveniently accommodated in plates, external fixators, and intramedullary implants. Larger data mining regarding various fracture locations, types, and morphology following the implementation of these sensors may offer a platform for further research and understanding of bone healing that can subsequently be used to optimise implant design/materials, thereby optimising patient recovery.

Sensor devices can track the development of callus to detect non-union or delayed healing issues early on. Designing intelligent, multifunctional technology that can track fracture healing, deliver biophysical therapeutic actuation, and enable implant–clinician contact through closed-loop feedback and individually tailored treatments managed by clinicians or surgeons is becoming more popular. It is quite likely that impedance monitoring utilising capacitive reactance changes will be used in conjunction with electrical stimulation to speed up bone mending. Yet, intelligent disturbance rejection to physiological changes and smart implants with intracorporeal excitations are required. Smart implants with the capacity to provide individualised treatments and monitor the healing of fracture targets are necessary for personalised therapeutic trajectories.

Nevertheless, with continuous advances in microprocessor technology, research designs, and additive manufacturing, the utilisation and application of SMART implants in the field of trauma and orthopaedic surgery are constantly growing. Mass production of such SMART implants will reduce overall production costs and see its use in routine clinical practice in the future and is likely to make a significant contribution in the next revolution termed 'Industry 5.0' which aims to focus on personalised patient-specific implants and devices [48].

Conclusions

SMART sensor technology may herald a new era in the field of orthopaedic trauma. With the potential to determine fracture healing rates and pre-mature implant failure accurately, it may serve as a feasible guide for orthopaedic surgeons thereby optimising patient care in the coming future.

Funding Nil.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human or animal subjects performed by the any of the authors.

Informed consent For this type of study informed consent is not required.

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