Improving Health Outcomes Through the Integration of Smart Body Sensors in Surgical Patient

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Abstract

Human health is assessed through various physiological indicators, including heart rate, blood pressure, body temperature, weight, urine analysis, and blood components. These markers help monitor liver, kidney, and heart health, glucose, lactate, electrolytes, and other biomarkers in biofluids. Continuous monitoring via wearable technology, implantable devices, and point-of-care solutions can reveal patterns in these parameters over time, crucial for an aging population with limited healthcare resources. This paper introduces the applications of integrating smart body sensors in surgical patients to improve health outcomes.

In surgical care, understanding the preoperative, perioperative, and postoperative stages is essential. Preoperative assessments often miss chronic illness changes, leading to postoperative complications. Innovative real-time tissue analysis tools are needed during surgery, and postoperative complications like surgical-site infections and anastomotic leakage require early detection.

Smart sensors integrated into medical devices can monitor critical complications like infections and sepsis, accelerating diagnostics and guiding treatment. Wearable ECGs, pulse oximeters, and bioimpedance imaging can track cardiac and lung function, while activity sensors and chemical sensors detect tissue ischemia and infections. These technologies enhance patient monitoring and improve outcomes, especially for high-risk patients.

Keywords: Body sensors, Arthroplasty, Neurosurgical outcomes, Technology, Orthopedics

Introduction

Human health is evaluated through a diverse array of physiological indicators. These metrics encompass heart rate, blood pressure, body temperature, weight, urine analysis, and blood components that help track markers related to liver, kidney, and heart health. Additionally, measurements of glucose, lactate, electrolytes, and various biomarkers found in biofluids are essential. It's also important to identify the presence of pathogens and viruses when necessary. Distinct health conditions are often defined by unique combinations of these physiological parameters, many of which may not be exclusive to a single illness[1]. Consequently, a comprehensive assessment of numerous parameters is crucial for gaining a complete picture of a patient's health. While this integrative approach is standard practice in hospitals employing various techniques, it is only recently gaining traction in the realm of wearable technology, implantable devices, and point-of-care solutions.

Continuous monitoring can reveal patterns in the evolution of these parameters through time and as a function of various conditions that would otherwise be overlooked by typical periodic sampling. With an aging population and increased life expectancy, a lack of health-care systems, and limited resources in many parts of the world, there is a need for patient-centric approaches to medicine, not only to decentralize health-care systems but to ensure worldwide access to inexpensive and reliable medical technologies[2].

Advances in fabrication techniques, electronics, and sensors and in the consumer-electronics industry, the rise of the internet of things, and the widespread availability of smart, portable devices have led to the development of a wide range of wearables for physiological measurement.

To create effective solutions, it is crucial to understand the entire surgical care continuum, encompassing the preoperative[3] , perioperative[4], and postoperative stages[5] , while identifying the key clinical deficiencies and challenges present in each phase. Various technologies and devices can play a role in enhancing the value throughout the surgical process. In the preoperative stage, lifestyle factors have a significant impact on the outcomes of major surgeries and the likelihood of postoperative complications[3]. Currently, the needs of high-risk patients remain unaddressed; alarmingly, four out of five postoperative fatalities occur within this demographic[5]. Changes in physiological conditions that indicate worsening chronic illnesses often go unnoticed by conventional preoperative assessments, which capture only a momentary snapshot, leading to inadequate preparation. As a result, these conditions may only become apparent after surgery, resulting in increased morbidity and extended hospital stays. For cancer patients undergoing neoadjuvant therapies before surgery, the temporary forms of imaging used to monitor tumor changes can complicate the timing of surgical interventions. In the perioperative phase, there is a pressing need for innovative, real-time tissue analysis tools that can assist surgeons during procedures[3].

Following surgery, various complications may arise, including surgical-site infections, catheter-associated sepsis, wound dehiscence, and colorectal anastomotic leakage. colorectal anastomotic leakage occurs due to failures in the anastomosis and is a significant contributor to mortality after colorectal procedures. Complications can also occur with vascular anastomosis—whether involving veins or arteries—especially in cases of free-tissue transfer that follow cancer resections or traumatic injuries. The severity of these complications can range from mild, requiring only oral antibiotics and careful monitoring in a hospital setting, to severe cases involving life-threatening sepsis that necessitate multiple surgical and radiological interventions. The early identification of these issues is crucial for enabling timely treatment. Unfortunately, these complications are often recognized too late; for example, colorectal anastomotic leakage can become evident anywhere from five to twelve days post-surgery, which may subsequently lead to surgical-site infections[6].

Sensors that have previously facilitated near-real-time continuous monitoring of blood pressure and cardiac function may pave the way for advanced processing in portable devices, along with prompt actions by healthcare teams. Future smart sensors, integrated within radiological fiducial markers used for cancer patients, could have the ability to monitor cellular activity and detect proteins associated with cellular proliferation. This innovative approach may lead to more precise evaluations of a patient's response to chemotherapy, empowering clinicians to make informed decisions on whether to adjust treatment plans or expedite surgical interventions. Furthermore, technologies designed for monitoring surgical wounds include localized sensing within the wound and the surrounding skin area. Sensors embedded in dressings or placed near surgical anastomoses could serve as early indicators of surgical site infections or tissue complications, prompting timely investigations and necessary clinical responses[7].

Healthcare professionals frequently utilize a variety of passive medical devices and instruments designed for basic functions that allow access to the human body and various biosamples. By incorporating sensing intelligence into these existing systems—without disrupting their traditional use and core functions—we can enhance their role in health care. For instance, devices such as central venous catheters, implantable ports, urine bags, and surgical drains can be equipped with sensors to monitor critical perioperative complications like infections and sepsis in real-time. This capability not only accelerates the diagnostic process but also provides essential prognostic data to guide treatment strategies. The impact of these advancements on patient monitoring in hospitals and during surgical procedures can be transformative[8].

Moreover, sensing technologies prove invaluable in identifying patients at medium and high risk, tracking behavioral changes, and enabling long-term remote monitoring after surgery and throughout the rehabilitation process. Integrating these sensing capabilities into the surgical workflow for both early detection and ongoing assessment could effectively tackle the challenges previously highlighted[8].

For instance, compact wearable ECG and pulse oximetry sensors can be employed throughout the perioperative process to monitor cardiac activity, while thoracic bioimpedance imaging offers insights into lung function. Sensors based on microelectromechanical systems enable the assessment of patient activity, rehabilitation, and lifestyle changes both prior to and following surgery. Additionally, near-infrared spectroscopy, bioimpedance, and chemical sensors can be utilized to monitor tissue ischemia around surgical sites during the perioperative and postoperative phases. Raman probes can be used to detect tissue infections, and (bio)chemical sensors can track critical biomarkers at the point of care, facilitating the detection of surgical site infections and ensuring overall homeostasis monitoring[8]. This paper aims to introduce application of integration of smart body sensors in surgical patient to improving health outcomes.

Neurosurgery

Postoperative monitoring plays an essential role in both routine and high-risk neurosurgical care. While vital signs offer crucial objective data immediately following surgery, the assessment of long-term outcomes is often influenced by subjective measures such as the visual analogue score and the oswestry disability index. Smart wear technology empowers healthcare providers to quantitatively analyze various aspects of patient recovery, including mobility and posture, both of which are vital for postoperative well-being[9]. Research has shown its effectiveness in conditions such as spinal stenosis, degenerative disc diseases, disc herniation, and spinal fusion procedures, revealing a significant correlation between patients' step counts and their overall recovery outcomes. A landmark study in 2019 by Kim and colleagues was one of the first to illustrate the effectiveness of the widely used fitbit charge (Google, San Francisco, California, USA) in tracking step counts among patients recovering from laminectomy surgery[10].

There is a noteworthy relationship between the number of steps taken and enhancements in both the visual analogue scale and oswestry disability index scores. In a similar vein, Ghent et al. utilized wearable accelerometers to track various metrics such as step count, walking speed, step length, and posture, paving the way for a new scoring system that showed a positive correlation with changes in oswestry disability index among patients undergoing lumbar surgery post-operation[11]. Concerning posture assessment, Wang et al. deployed a tri-axis accelerometer on five patients who had cervical spine injuries, achieving an impressive 100% accuracy in differentiating various spinal postures[12]. Additionally, smart clothing and belts have demonstrated potential in accurately identifying poor posture and even providing real-time feedback through vibratory signals to users. While much of the research has centered on spinal surgery, these technological advancements hold promise for application in other areas of neurosurgery. For instance, in an endovascular context, a study involving postoperative carotid endarterectomy patients equipped with an accelerometer-integrated belt revealed objective improvements in gait following surgery[13].

Furthermore, an assessment of a smartwatch designed for monitoring patients following transsphenoidal surgery revealed excellent patient compliance along with significant physiological changes observed in the postoperative period. Overall, this indicates a notable potential for SmartWear in the care of neurosurgical patients post-surgery. Nonetheless, additional studies of these devices in contexts beyond spinal surgery are necessary[14].

Spine surgery

In the field of minimally-invasive and percutaneous spine surgeries, the incorporation of a Raman micro-spectroscopic system into spinal implants and surgical tools presents an innovative strategy to protect nerve roots and other neural tissues from damage caused by medical procedures[15]. The success of this system has been thoroughly documented in several animal studies, showcasing its potential to improve surgical safety[16]. SMART spinal implants are designed to offer significant benefits in monitoring spinal fusion, especially in cases of extensive instrumented arthrodesis. Strain gauges have been utilized on the laminae of vertebrae and posterior spinal devices to evaluate the progress of fusion. As the fusion process unfolds, the strain on the fusion rod diminishes, while the peak bone strain initially rises before stabilizing. These spinal implants come in both pedicle-based and inter-body designs, providing flexibility for various surgical uses.

The Fowler-Nordheim sensor-data logger is a groundbreaking device that functions independently of a battery, drawing energy from a piezoelectric transducer. This energy is used to operate the sensor, which simultaneously tracks the progress of spinal fusion. Innovations in sensor technology like this not only improve monitoring abilities but also bolster the efficacy and safety of spinal surgeries[17].

Dermatological surgery

In dermatological surgery, keeping track of wound healing is vital for assessing the effectiveness of treatments and achieving the best possible healing results. Prompt and precise evaluation of wound healing is necessary to avert complications such as infections, slow recovery, and scarring. Traditional approaches, including visual assessments and manual measurements, can be subjective and labor-intensive, often failing to reflect the dynamic changes in the wound as it heals. Advanced techniques like confocal laser scanning microscopy and spectroscopy provide quantitative imaging capabilities that can identify microscopic alterations in the structure of the epidermis and dermis. Nonetheless, these methods typically necessitate that patients remain still during the procedure[18].

To overcome these challenges, advanced sensor devices dedicated to wound monitoring have emerged as a highly effective solution. These devices offer objective, real-time, and continuous data regarding key wound healing indicators, such as temperature and pH levels. Hattori et al. developed a groundbreaking epidermal electronics system (EES) capable of recording the dynamic changes in temperature and thermal conductivity of skin tissue, thereby enhancing our understanding of the healing process[19]. Additionally, the noninvasive evaluation of wound pH proves beneficial in assessing the wound's condition and measuring the success of treatment strategies, as maintaining a slightly acidic pH is crucial for optimal healing; it facilitates collagen formation, boosts fibroblast activity, and restricts bacterial growth[20].

An innovative smart dressing has created that allows for the real-time monitoring of wound pH levels, enabling the assessment of wound health without interfering with the wound bed[21]. In a similar vein, Kalasin and co-authors introduced a non-invasive wearable system designed for monitoring wounds remotely. This system, which operates on a binary model, consists of a flexible artificial intelligence wearable sensor and a smart bandage that communicate through radio frequency identification technology. This advanced contactless healthcare solution leverages AI to analyze the healing stages of inflammatory skin lesions, categorizing them into phases of inflammation, proliferation, or remodeling. Such a system provides dermatologists with objective metrics for evaluating the effectiveness of treatments and informing medication strategies[22].

Cardiac surgery

The incorporation of smart wearable sensors in the rehabilitation of cardiac surgery patients has demonstrated encouraging results in improving patient outcomes[23]. These innovative devices are capable of continuously monitoring vital signs such as heart rate and oxygen saturation, physical activity levels, and overall recovery, generating valuable insights that can inform individualized care plans. The use of wearable technology notably enhances adherence to exercise programs and allows for the early detection of potential complications. This technology has the power to transform cardiac rehabilitation practices. For example, sensors integrated into smart clothing can monitor heart rate variability, breathing patterns, and movement, providing real-time feedback and enabling adjustments to rehabilitation strategies [24]. Such continuous monitoring helps prevent overexertion and ensures that patients progress in a safe and effective manner. In addition, applying machine learning algorithms to the data gathered from these sensors can help forecast recovery pathways and pinpoint patients who might be at higher risk for negative outcomes. Wearable sensors can identify those who may require extra assistance or specific interventions.

It is also important to acknowledge the social dimension of recovery. Wearable devices can act as a platform for virtual support communities, allowing patients to share their experiences, gain encouragement, and maintain motivation. This aspect is especially beneficial for individuals facing mobility challenges or those residing in remote areas.

In summary, the use of smart wearable sensors in the rehabilitation of cardiac surgery patients is a dynamic and rapidly advancing field with significant potential to enhance patient outcomes. As technology evolves, these devices are poised to become a fundamental component of the cardiac rehabilitation process, delivering personalized, continuous, and proactive care[25].

Arthroplasty surgery

Impaired physical activity in the early postoperative period following total joint arthroplasty may indicate potential complications and contribute to patient dissatisfaction [26]. Traditional methods for assessing activity, including timed walk tests and patient-reported questionnaires, necessitate active administration and typically provide data at a single time point[27]. In contrast, commercially available wearable activity sensors offer a viable solution for the passive monitoring of patient activity. These devices can effectively track metrics such as step counts, distance walked, and caloric expenditure associated with exercise intensity in the context of total joint arthroplasty[28]. Consequently, these sensors may serve as valuable tools for the early detection of postoperative complications following total joint arthroplasty.

Arthroplasty surgery can lead to a range of complications, with prosthetic loosening being particularly noteworthy. This issue can be divided into two primary types: aseptic loosening, which occurs due to mechanical wear and tear, and septic loosening, which is linked to infections related to the prosthetic device [29]. Recent innovations in sensor technology have shown great potential in accurately detecting these forms of loosening. Notably, a mechano-acoustic sensor, integrated into the implant and powered by an external coil, has proven effective in recognizing both prosthetic loosening and successful osteointegration with remarkable precision[30]. This advancement offers considerable benefits for monitoring patients over time.

Information obtained from these sensors can be applied for real-time gait monitoring in individuals who have undergone total knee arthroplasty) and total hip arthroplasty). This kind of analysis is essential for evaluating a patient's recovery and overall functionality following surgery[31].

After knee replacement surgery, noticeable enhancement in walking can be seen during movements like standing up or sitting down. Usually, to accurately evaluate these improvements, a specialized gait lab is needed, which can be expensive, cumbersome, and not always feasible. However, using portable sensors to measure walking difficulties after knee surgery allows for ongoing tracking of the healing process. This method can be applied through a consistent set of activities both before the surgery and at regular points up to twenty-four weeks afterward. A small, ear-mounted sensor could offer important information about recovery after the operation and help pinpoint patients who may not be progressing as expected, thus enabling prompt medical assessment and intervention[32].

Trauma surgery

In the field of trauma surgery, new and creative methods are being introduced. A magnetic sensor technology has been created that includes a magnet placed inside the locking hole of an intramedullary nail[33]. This setup helps guide sensors attached to the drill, ensuring that locking bolts are inserted accurately while reducing exposure to radiation. Furthermore, pressure sensors made from polydimethylsiloxane are used to evaluate how forces, such as compression and tension, are distributed during surgeries for olecranon fractures[34]. Additionally, research has shown the benefits of using instrumentations powered by sensor technology, which significantly improves accuracy in various trauma surgical procedures. For example, the McGinley Orthopedics "IntelliSense"™ system demonstrates how advanced drills can enhance directional precision and depth perception, all while lowering radiation risks for surgeons[35].

Sensor technology has become an essential asset in tracking the healing of bones and the formation of calluses during patient recovery. Implants equipped with sensor systems feature an external antenna that emits electromagnetic waves, tailored to the structural qualities of the neighboring bone. This setup allows for the detection of changes in the distribution of loads between the callus and the implant[36]. As the natural healing of fractures occurs, the weight borne by the implant gradually transfers to the callus. By taking regular measurements of these load changes, enabled by sensor technology, it becomes possible to identify cases of non-unions at an early stage.

Fiber bragg grating sensors were integrated into implants to monitor the strength and strain of bones at the ends of fractures during different stages of healing. The primary aim was to determine the best moment to safely resume weight-bearing activities. Likewise, piezo-floating gate sensors have proven effective in detecting non-unions much sooner than traditional methods. In studies with animal subjects, signs of non-unions were observed as early as 21 days after a fracture, highlighting the promising capabilities of sensor-equipped implants for prompt fracture assessment, especially in challenging cases known for slow recovery, such as fractures of the distal tibia, scaphoid, neck of the femur, and talus[37].

In addition, sensors integrated into Ilizarov ring fixators and hexapod devices have been utilized to track distraction osteogenesis, measure stresses at the ends of bones, analyze the quality of callus formation, and confirm the success of angular adjustments. These sensors offer ongoing, dependable, and objective observation of bone healing, something that current methods cannot provide. As a result, they play a crucial role in identifying the best time for the removal of implants. Furthermore, Marmor's research investigated the impact of wearable activity monitorsin evaluating patients' functional capabilities both before and after injuries, further highlighting the importance of incorporating sensor technology into medical practices[38].

Abdominal surgery

Healing after surgery on the abdomen presents a significant risk period, with nearly one in three individuals experiencing a serious complication within a month of their operation. Delays in identifying these issues and the subsequent lag in providing necessary care can lead to further preventable injuries[39]. Numerous research efforts have pointed out that the inability to save patients from complications significantly contributes to mortality around the time of surgery, underscoring the critical need for diligent monitoring after the procedure. Even for those who manage to avoid severe complications, the recovery process can still be quite tough[40]. Contemporary protocols aimed at enhancing recovery, which are based on solid evidence, have demonstrated their effectiveness in promoting recovery, minimizing complications, and shortening the length of hospital stays. However, it is not uncommon for deviations from these established protocols to occur, and such lapses are frequently linked to worse outcomes.

Prompt postoperative movement is a fundamental principle of enhanced recovery after surgery protocols across all abdominal surgical fields. It presents a potential opportunity for intervention that could expedite patient recovery by leveraging digital technologies. Multiple studies employed wearable devices to track physical activity following surgery, whether through passive monitoring or as part of initiatives designed to boost mobility[41]. Various research findings indicate that patients who are less active—both prior to and following surgery—face an increased risk of complications, readmissions, and other negative health outcomes. However, it remains uncertain to what degree these observations reflect the patients' initial frailty rather than a potentially adjustable factor influencing perioperative risks[41].

Adjusting a patient's postoperative activity levels in relation to their preoperative baseline may provide a more precise approach to risk evaluation. Moreover, the analysis of mobilization "patterns," as proposed by Iida et al., could yield deeper insights into forecasting specific postoperative complications[42].

The ability to predict complications based on physical activity in real-time, rather than looking back retrospectively, remains ambiguous and warrants further focused research. Providing targeted feedback from physical activity data collected by wearables has the potential to influence behaviors and decision-making for both patients and healthcare providers, and the most effective ways to facilitate this should be investigated. Additionally, several technical hurdles concerning the use of wearable activity trackers to oversee postoperative recovery still need to be addressed.

Movement patterns in postoperative patients may involve shorter, less intentional steps, and there are concerns about the reliability of sensors in this demographic, as very few commercial activity monitors have been validated for use in hospitalized or postoperative individuals[43]. More advanced methods than merely counting steps may be essential for accurately assessing postoperative physical activity. Furthermore, doubts have been raised about the reliability of wrist-worn activity measurements, which may differ based on where the device is positioned—be it the wrist, ankle, or hip[44].

Conclusions
The adoption of smart body sensors is swiftly gaining traction in outpatient environments to oversee and care for surgical patients. these gadgets enable timely detection, reliable diagnosis, and targeted treatment. Nevertheless, despite the bright prospects for smartwear, challenges like system integration and data security need to be tackled.

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