



Non-invasive smart implants in healthcare: Redefining healthcare services delivery through sensors and emerging digital health technologies

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ABSTRACT

The adoption of non-invasive smart implants is inevitable due to recent technological advancements in smart implants and the increasing demand to provide pervasive and personalized care. The integration of non-invasive smart implants presents unprecedented opportunities for effective disease prevention, real-time health data collection, early detection of diseases, real-time monitoring of chronic diseases, virtual patient care, patient-tailored treatment, and minimally invasive management of diseases. Even though the research work in this area is nascent, this study presents the potential benefits and use of non-invasive smart implants in healthcare while reflecting on the potential challenges and limitations of their utilization. With current technological advancements, the adoption of non-invasive smart implants is regaining momentum in managing chronic conditions and diseases such as cancer, cardiovascular diseases, cognitive impairment; orthopedic surgery, dental surgery; and managing and remotely monitoring infectious diseases such as the novel coronavirus disease 2019 (COVID-19). However, the full adoption and utilization of non-invasive smart implants still encounter barriers such as lack of policies and frameworks regulating their use, limited memory space, health consequences and implants' failure, clinical challenges, health hazards imposed by non-invasive smart implants, health data security, and privacy risks. Therefore, there is a need for robust security and privacy measures as well as the formulation of policies guiding the development and use of non-invasive smart implants. With the gained experience from smart implants, the next generation of non-invasive smart implants may include sophisticated modern computational techniques that can analyze health data and suggest adequate therapeutic actions.

1. Introduction

The emergence of COVID-19 calls for drastic measures and has expedited the utilization of digital technologies in health care systems globally. Advances in emerging technologies expedite digital transformation in health systems, from traditional healthcare to digitized, robust virtual health care guided by distributed patient-centric approach. Healthcare is undergoing a rapid transformation from conventional

hospitals and specialist-focused approaches to distributed patient-centric approaches. Among various technologies, sensors and smart wearable devices have been promising to deliver remote health care services and smart healthcare. Through such technologies, healthcare systems witnessed the development and deployment of diverse digital health applications such as smart medication, telemedicine [1], assisted living, as well as remote and onsite monitoring of assets in hospitals, as well as patients' behavioral change, and treatment compliance [2]. For instance,

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smart devices, including smart bands, smartwatches, smart clothes, smartphones, wireless smart glucometers, and wireless blood pressure monitors, have been utilized during COVID-19 for virtual health monitoring. Health data such as heart rate, blood pressure, and blood sugar level are generally captured with smart sensory devices remotely and transmitted as electrical pulses for further processing. Smart sensory devices have been widely used to capture and translate health data into observable electrical impulses [3]. Such technological advancements continue to transform health systems globally and unlock new opportunities to provide personalized care to assist healthcare professionals [4], especially during pandemics like COVID-19.

Sensors, especially biosensors and nanosensors, are increasingly becoming indispensable resources for monitoring daily life activities in the medical field [5] for improved clinical diagnostics and monitoring biological molecules [6]. Smart wearables can communicate with other devices and transmit health information. The pervasiveness and ubiquitousness of smartphones integrated with sensors present unprecedented opportunities to develop feasible and robust health interventions. For instance, smart wearable devices such as smartwatches, wrist bands, eyewear, headsets, earbuds, body straps, foot and hand-worn devices, and smart jewellery have been utilized for different health applications [7].

1.1. Contribution of the study

There has been significant progress in integrating sensors in smart wearable devices. However, the use of sensors in implantable devices has been predominantly rigid, as they were conceived in the early 1970s when the first hearing aid was developed [8]. Their importance in healthcare systems has been growing rapidly recently and has attracted more attention in the medical field. Now the use of biosensors and nanosensors is slowly gaining momentum in the development of implantable medical devices, which ultimately led to the introduction of non-invasive smart implants in healthcare for diagnostic and therapeutic purposes. Non-invasive smart medical devices are slowly utilized for multipurpose and interact with physiological processes such as the heartbeat and mediate sensing and local stimulation, data recording and even drug delivery. Several scholars, including [9–12] posit that non-invasive smart medical devices play a crucial role in healthcare, especially when making clinical decisions, and potentially support personalized health care for effective diagnosis and therapy, yet their implementation faces significant resistance, challenges and consequently limit their use thus far. Notably, there is limited literature on the potential capabilities of non-invasive smart implants in healthcare. However, the utilization of smart wearable devices to tackle COVID-19 and other infectious diseases has made it possible to circumvent resistance towards the adoption of non-invasive smart implants in healthcare, though it is a nascent research area. There is limited literature on the application and utilization of non-invasive smart implants in healthcare. Therefore, this paper presents the capabilities and significance of non-invasive smart implants, various application areas as well as the challenges and limitations hindering their use in healthcare. The paper also provides recommendations for the effective use of non-invasive smart implants in healthcare for improving service delivery and personalized health care. Therefore, this study aimed to achieve the following research objectives:

- i) Identify and explore the capabilities and significance of non-invasive smart implants in healthcare service delivery.
- ii) Identify various applications of non-invasive smart implants in healthcare and their respective challenges and limitations.
- iii) Propose recommendations for the challenges and limitations identified in (ii)

The remainder of the paper is structured as follows: Section 2 explains the methodology adopted by the study. The significance of non-invasive

smart implants in the provision of personalized healthcare is presented in Section 3. Section 4 outlines the potential applications of non-invasive smart implants in the various continuum of healthcare. Section 5 presents the challenges and limitations of using non-invasive smart implants in healthcare. The recommendations and future opportunities of non-invasive smart implants are presented in Section 6. Finally, the conclusion and future works are presented in Section 7.

2. Methodology

The study applied rapid review of scientific published literature on non-invasive smart implants in healthcare and healthcare delivery through smart sensors and emerging digital health technologies. We searched the following prominent electronic databases for relevant articles - PubMed, IEEE Xplore, Google Scholar, Scopus and Science Direct, using the following keywords, “*smart implants*” OR “*non-invasive smart sensors*” OR “*smart sensors*” AND “*healthcare*” OR “*emerging health technologies*” OR “*virtual healthcare*”. We structured the search in the same way across all the databases to maintain consistency. We selected peer-reviewed articles, non-opinion articles that were either written in the English language or had an English translation. We excluded reviews, opinions, letters to editors, commentaries, conference abstracts and articles on electronic health alone that did not focus on emerging digital health technologies, smart implants, smart sensors or non-invasive sensors.

3. Significance of non-invasive smart implants in the provision of personalized care

The escalation of chronic illnesses and conditions, such as sleeping disorders, cancer, cardiovascular diseases, cognitive impairment [13], functional decline and emotional problems [14], as well as the costs associated with managing chronic symptoms, and lifestyle-induced diseases, presents unprecedented health challenges globally. Instead of relying on conventional interventions that are sometimes affected by the imposed restrictions (e.g. COVID-19 regulations) [15], the future of sustainable smart health interventions depends on technologies such as non-invasive smart implants that focus on the provision of virtual healthcare services centred on effective disease prevention, real-time health data collections, early detection of diseases, real-time monitoring of chronic diseases, patient-tailored treatment and minimally invasive management of diseases, as shown in Fig. 1.

Smart health monitoring for the tracking and diagnosis of physiological issues, early disease detection, prognostication and prevention, relies on ubiquitous and unobtrusive monitoring digital health systems [13] and most importantly, sensor types and data modelling algorithms [16]. Sensors, especially biosensors and nanosensors, play significant roles in the development and deployment of non-invasive smart implants in the continuum of care [17]. In addition, biosensors and nanosensors can be used in electrocardiograms, electromyography, monitoring of blood pressure, electroencephalography, photoplethysmography, heart sound, respiration, sleep, and motion monitoring. The integration of biosensors and nanosensors in non-invasive smart implants can be scientifically and clinically useful for better monitoring of real-time, long-distance, and dynamic physiological, emotional and pathological processes through the use of microfabrication and nanofabrication of biocompatible materials. Non-invasive smart implants can be used in cardiac resynchronization therapy devices, pacemakers, orthopedic, hip replacements, dental therapy, breast implants and cosmetic therapy among others [18].

4. Potential applications of non-smart implants in healthcare

Smart implants have brought unprecedented opportunities to transform healthcare services delivery to move towards pervasive and personalized care through the adoption of non-smart implants.

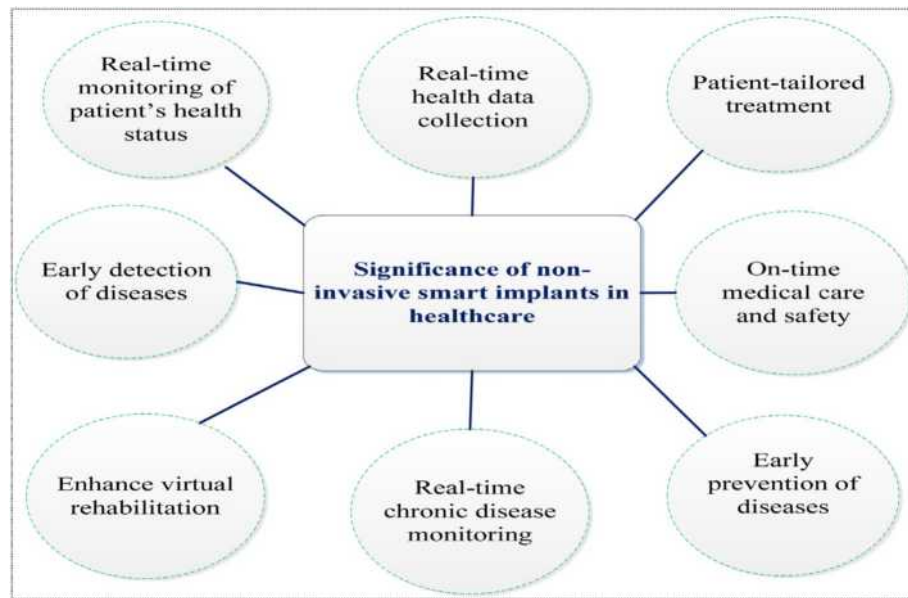


Fig. 1. Significance and capabilities of non-invasive smart implants in healthcare.

Table 1 shows that non-invasive smart implants can be potentially used in managing and monitoring chronic diseases such as cardiovascular diseases, orthopedic surgery, dental surgery; and managing and remotely monitoring infectious diseases, as shown in Fig. 2. These application areas are further explained in the following subsections.

a. Chronic heart disease

A study conducted by Bussooa et al. [9] reported that smart implants such as coronary stents and endoSure sensors play a tremendous role in managing and monitoring cardiovascular diseases. In addition, implantable medical devices allow for the observation of physiological activities such as heartbeat [27] as well as the recording of electrocardiogram measurements [28] from within the body. This is important for observatory purposes in patients with cardiovascular heart diseases. As is the case in the treatment of other diseases, the use of non-invasive implants to treat cardiovascular diseases has not been without shortcomings. There are issues of powering the implants as well as manufacturing them at appropriate sizes for their use as vascular stents [29]. Although batteries are a reliable source of power, the major issue with their use is that they take a considerable amount of space that is required by the implant. To overcome the issue of powering the implants, wireless powering has been suggested, where, rather than using batteries, electric coils can be employed [30]. Through this system, an electric coil can be embedded inside the body with the implant so that it can receive energy from another coil outside the body.

b. Orthopedic surgery

The use of orthopedic implants has provided relief for people suffering from mobility complications. These medical devices have multiple uses such as the replacement of joints such as the knee, elbow, and hip, shoulder replacement, bone replacement and the functional restoration of damaged structures [31]. Despite this, movement can negatively affect the implanted devices. For example, as reported by Burny et al. [32], an implant used to treat fractures of the femur can sustain so much pressure from body weight when one is walking. This can result in the failure of the implant if the weight exerted on it is greater than its elastic limit. This, therefore, necessitates constant monitoring of the strain on the implant to avoid its deterioration. Wireless sensors can be implanted along with orthopedic devices to relay information

wirelessly to external monitoring equipment [31]. These sensors, therefore, provide data on the status of the biological tissues around the implant. It has been reported that forces that are applied on orthopedic implants can be measured using internal strain gauges [33].

c. Dental surgery

Dental implant technology has been in use since the end of the last century and helps not only in the restoration of function but also in appearance enhancement [34]. Intramucosal implants are dental implants that are placed in the oral mucosa using the mucosa as a site of attachment for the metal inserts [35]. In addition to trauma, dental implant surgeries require longer recovery periods and can lead to biological and mechanical complications [36,37]. Dental implants are prone to preload, which is a force caused by the application of torque on the screw which causes tension and elongation [38]. Post dental surgery abutment screw loosening can cause complications such as the fracturing of the screw and gingival inflammation [39]. Although numerous studies have been undertaken both at an experimental and clinical level, the precise cause of abutment screw loosening is yet to be completely elucidated [25]. It has however been suggested that the increment in torque, retightening of the screw and the use of diamond-like carbon coating on the screw can help alleviate the problem of screw loosening [40,41].

d. Infectious diseases

The advent of COVID-19 has reminded the medical world of the need for innovative and effective approaches against viral diseases. The most effective strategy to fight against infectious diseases such as COVID-19 is early detection to minimize the spread of these diseases. Biosensors have been applied against a variety of infectious diseases such as HIV, Ebola, influenza and others [42]. The integration of smart materials and biosensors have afforded the early and perhaps more robust and accurate detection of viruses such as SARS-CoV-2. Carbon and graphene-based nanomaterials have been used to improve the detection of the coronavirus even at extremely low concentrations. Although polymers are ideal for use in living systems because of their malleability and small weight, they have poor mechanical strength. It is for this reason that carbon-based materials are gaining momentum because they have good mechanical strength and are highly flexible [43].

Table 1
Potential application of non-smart implants in healthcare.

Reference	Smart implant	Functions	Application	Challenges and limitations
[9]	Coronary Stents and endoSure sensor	Self-reporting cardiovascular stents	Cardiovascular disease	- Costs and miniaturizing the battery - Integrating electronic components onto a stent is a major challenge because these components need to resist stent crimping procedures and stent expansion.
[19]	Dental and orthopedic implant	Evaluation and monitoring of osseointegration	Dental and orthopedic surgery	- The stability of implants is a major issue in dentistry and orthopedic - Care provider's experience and skills, as well as standardization of smart implants, is difficult
[20]	Smart Orthopedic Implants	Detection of loosening for hip implants, assessment of bone healing, spinal fusion monitoring, force measurements in knee implants and diagnosis of orthopedic implant failure	Orthopedic	- Biocompatibility issues - The wireless interface between a wireless sensor implanted next to an orthopedic prosthesis has been reported - Power requirements of wireless sensors for smart orthopedic implants
[21]	Load-sensing implants	Real-time health monitoring	Orthopedic	- Implantability and biomechanical non-obtrusiveness - Wireless interfacing capacity
[10]	Smart implant	Progression of fracture healing, data acquisition and remote monitoring	Orthopedic	- Regulatory hurdles - Misfit to reimbursement schemes
[22]	Ultra-high molecular weight polyethylene (UHMWPE) insert	Resection of the femur and tibia and replacing them with metal components	Orthopedic surgeries (Total knee arthroplasty (TKA))	- The survival rate of the implant may be short-lived due to knee forces depending on the weight of the patient. The range of motion may be affected by TKA procedure - It is difficult to estimate forces at the tibiofemoral and patellofemoral joints due to muscle complexity - The patellofemoral joint is small, allowing little room for sensor placement
[23]	Prosthetic implant	Physiological antetorsion	Orthopedic surgeries -Total hip arthroplasty (THA)	- Postoperative anterior dislocation of THA can occur - The range of motion of the joint post operation may be inhibited by stem antetorsion - THA can be costly because it involves imaging and computer-assisted 2D and 3D software
[24]	Interbody cage implant	For the cervical spine, the implant is inserted in the intervertebral disk space with an anterior cervical plate affixed to the vertebral bodies while for the lumbar spine, the implant is placed in the intervertebral space after a laminectomy	Orthopedic surgeries (Spinal fusion surgery)	- Placing the implant is difficult due to the complexity of spine muscles - Biomechanical properties of the spine are not well understood making spinal fusion surgery a complicated procedure - There is a need to understand postoperative forces that implants are subjected to such as flexion, torsion, and bending to improve implant design and post-operation rehabilitation procedures
[25]	Endosteal implant Subperiosteal implant	Endosteal implantation involves the insertion of a pin, blade, or screw into the jawbone while subperiosteal implantation involves custom-made metal frames that are mainly used where there is insufficient bone	Dental surgery	- Dental movement can cause mechanical issues such as screw loosening or even implant fracture - Dental implants are very costly - Other complications such as abutment screw loosening or fracture, porcelain fracture, crown loosening can occur - Dental implants require a longer treatment time - Screw deformation can occur
[26]	Electrosensitive materials, wearable intelligent materials, Photosensitive materials and Nanomaterials	Carbon and graphene-based nanomaterials integrated with biosensors. FET sensor coated with graphene sheets and functionalized with antibodies against SARS-CoV-2 spike protein allowing virus detection at very low concentrations.	COVID-19	- Both carbon and graphene nanomaterials are expensive to produce - Graphene may contain some impurities - Carbon nanomaterials can be toxic to biological systems - There is a need for more studies on the toxicity of carbon nanomaterials and their pharmacokinetics

The integration of non-invasive smart implants and sensors is becoming pervasive and will eventually alter traditional healthcare provision. This is mainly because non-invasive implantable medical devices offer a viable alternative to medical conditions that cannot be solved by medication alone. Non-invasive smart implants allow personalized diagnosis and disease treatment that is specific to each patient, as highlighted in Table 2. Additionally, they allow the continuous monitoring of a patient's health status. These smart implants offer around-the-clock patient health monitoring irrespective of location, weather, patient

mobility or patient mental state, something that cannot be attributed to conventional medicine. Sensors integrated into non-invasive smart implants allows the assessment of physiological activity in patients in real-time. Smart implants, thanks to the integrated sensors, are important in disease prevention, diagnosis, control, and treatment. Costs associated with traditional health care continue to increase, making the low-cost non-invasive smart implants even more appealing. Because of the above factors, the routine clinical application of non-invasive smart implant-based sensing devices is becoming more and more imminent.

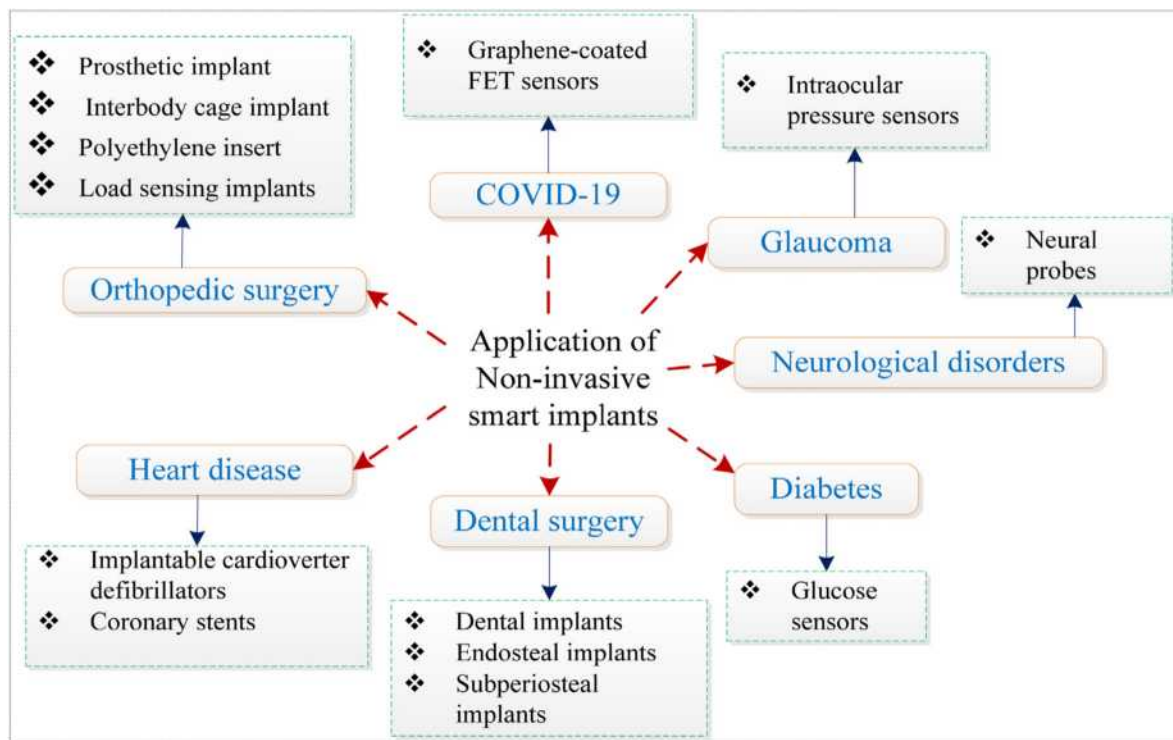


Fig. 2. Applications of non-invasive smart implants.

Table 2

Advantages and disadvantages of some non-invasive smart implants.

Smart implant	Function	Advantages	Disadvantages	Reference
Glucose monitoring sensors	Monitoring blood glucose level captures rapid changes in glucose levels and accurate readings of glucose levels.	- Continuous glucose monitoring - Time-efficient - Very reliable - Non-invasive - Pain-free - Cost-effective	- Need frequent calibration - May cause skin irritation - Securing device in the body may cause discomfort	[44]
Intraocular pressure sensors	Monitoring eye pressure level	- Stable - Reliable and portable - Cost-effective - Simple design - Continuous monitoring of intraocular pressure	- Need frequent calibration - Securing device in the body may cause discomfort	[45]
Implantable cardioverter-defibrillators	Monitoring and restoring a heartbeat	- Continuous monitoring of heart rate - Restoration of heart rate to normalcy - Prevention of arrhythmic episodes - Prevention of ventricular arrhythmias-related deaths	- Infection may occur at the site of implantation - Patient may need extra therapy	[46]
Neural probes	Monitoring and stimulating brain activity	- Can be made to have the self-diagnostic capability - Records high quality neural signals - Reduction in inflammation responses in polymer-based probes - Can stimulate living brain tissue - Polymer-based probes allow stable chronic recordings	- Susceptible to buckling or bending during insertion - High flexibility makes it difficult to insert into the brain	[47]
Orthopaedic arthroplasty sensor implants	Monitoring orthopaedic implant activity	- Feedback on the implant performance <i>in vivo</i> - Monitoring of patient's clinical recovery alignment - Load bearing data collection - Provision of post implantation data - Early detection of wear - Output data used to improve implant design	- Can be costly - Digital security laws need to be applied for patient data security - Approval by regulatory authorities needed for widespread use	[48]

Therefore, it is almost inevitable that non-invasive smart implant technology, in synergy with the integrated sensors, will be used ubiquitously in clinical settings and therefore become commercially viable.

5. Comparison of the current non-invasive smart implants sensing devices and the other type of nanomaterials based sensing devices

At the same time that sensor-based non-invasive smart implants are becoming more pervasive, so are nanosensors. Nanomaterials such as graphene and carbon are now being integrated with biosensors to make non-invasive smart implant sensing devices. Many examples of such integrated devices exist today. A chemical gas sensor was developed through in situ polymerization by preparing a conducting film based on a nanostructured polyaniline-coated carbon nanotube network [48]. This sensor had 85% transparency and demonstrated good flexibility and efficient sensing of portable gas at room temperature. Most non-nanomaterial based non-invasive smart implants utilize polymers which have been shown to have poor mechanical strength [49]. In contrast, nanomaterial-based sensing devices, mainly due to carbon, are mechanically strong and flexible. Carbon nanotubes allow superior electron transport and collection, which allows more flexibility and better sensing which may prove imperative during the integration of chemical gas sensors into optoelectronic and wearable devices easily and cost-effectively [50]. The high sensitivity of nanomaterial-based non-invasive implants have been shown to allow better detection of viruses such as SARS-CoV-2 more accurately and at very low concentrations owing to the high sensitivity afforded by nanomaterials such as carbon.

Another gas sensor that was developed by the facile hydrothermal method, and based on ultralong MoO₃ nanobelts, has been shown to have both high gas sensing capability of trimethylamine and high flexibility at lower temperatures than those required by metal oxide sensors [51]. High sensing capacity of the sensor was more for trimethylamine than other gases such as methanol, ethanol, and acetone. Unlike biosensors used in non-invasive implant technology, MoO₃ nanobelts have a networked structure that may enhance the diffusion of gases. Nanomaterials also allow quick electron transport which is contributory to their flexibility that is not common in non-invasive smart implant sensing devices.

The exploration of non-invasive smart implants and biosensors for biomedical and health purposes remains a very active research avenue. A microfluidic biosensor based on the nanomaterial MXene was developed for the analysis of whole blood and its applications in hemodialysis [52]. The MXene biosensor allows the analysis of different target compounds in the blood such as uric acid and urea all at the same time. Therefore, this new innovative sensor allows the reliable and continuous monitoring of blood components, an advantage that is shared with most non-invasive smart implants such as intraocular pressure sensors [45], cardioverter defibrillators [46] and glucose level sensors [44] which monitor intraocular pressure, heart rate and glucose level respectively in a continuous fashion. Continuous monitoring allows the real-time identification of any physiological anomalies which allows rapid medical treatment. Similar to the use of non-invasive smart implant sensing devices, the use of MXene electrochemical microfluidic microchip for analysis of whole blood does not require sample pre-treatment [52] which is very time efficient.

Nanomaterial-based sensing technology, especially carbon-made materials, need further research because a lot more still has to be learnt about them. Two-dimensional nanomaterial-based sensors are some of the advancements in non-invasive smart implant technology. Nanomaterials such as graphene as well as some metal oxides have been shown to have ideal properties for making very efficient sensors for human health monitoring as well as monitoring of environmental factors [53]. Nanomaterial-based sensors, like non-invasive smart implants, are innovations aimed at circumventing the costs associated with conventional medicine. These innovations are also an attempt to minimize

ambient noise and increase sensitivity. The use of nanomaterials such as graphene is dependent on the properties of these materials [53] such as the size of the material, flexibility and compatibility with electronic devices. Therefore, the structural properties of nanomaterials afford them to be used in sensor development perhaps in ways that other materials would not be suitable.

Fig. 3 shows the schematic presentation of orthopaedic non-invasive smart implant sensor technology during total knee arthroplasty. Radio-frequency transmits signals from the implant smart sensor to the exterior of the body into computer servers and databases. This data is then analysed, and appropriate action is taken.

6. Challenges and limitations hindering the use of non-invasive smart implants in healthcare

Generally, non-invasive smart implants provide many advantages that are not common in the traditional healthcare system. The obvious of these is the *in vivo* measuring and monitoring of physiological activities through the assistance of wireless communication. Other benefits include affordability, constant monitoring of disease progression, real-time relay of patient's health status, personalized disease treatment and many other benefits. Despite the promising benefits of non-invasive smart implants to move towards pervasive and personalized care, their adoption and utilization in healthcare is not immune to challenges and limitations. Such hindrances are discussed below.

a. Lack of policies and framework regulating the use of non-invasive smart implants

Despite the promising benefits of non-invasive smart implants in healthcare, the clinical implementation and feasibility of this technology may encounter some challenges due to the lack of clear policies and frameworks [10]. By considering the time taken to recognize the importance of the first generation of instrumented implants, the adoption of non-invasive smart implants in healthcare will face policy and regulatory hindrances despite the use of smart implants in dentistry and orthopedics.

b. Limited Memory Space

Health data collected with biosensors and nanosensors in non-invasive smart implants ought to be buffered inside the device itself before being transmitted to an external system. However, considering the total size of a non-invasive smart implant (small), all things considered, such devices cannot have the option to store huge amounts of data at an instance. Consequently, non-invasive smart implants may be unable to store the sensed information, even temporarily. Thus, the entire amount of data storable in a biosensor or nano-memory relies upon its size. In addition, technical challenges including power consumption, communication range, data transfer rates, size, robustness and cost, may affect the implementation of non-invasive smart implants [22].

c. Health consequences and implants failure

Conventionally, non-invasive smart implants use electronic or electromechanical sensors, which can present some drawbacks such as sensitivity to misalignments, electromagnetic fields sensitivity, lower compactness, the necessity of frequent calibration and, in some cases, hysteresis and drift on the sensor response [21] which can lead to implant failure [20].

d. Health hazards imposed by non-invasive smart implants

Although non-invasive smart implant technology has a promising future and the potential to solve many healthcare issues such as cancer diagnosis and regular check-ups and provision of medicines as and when

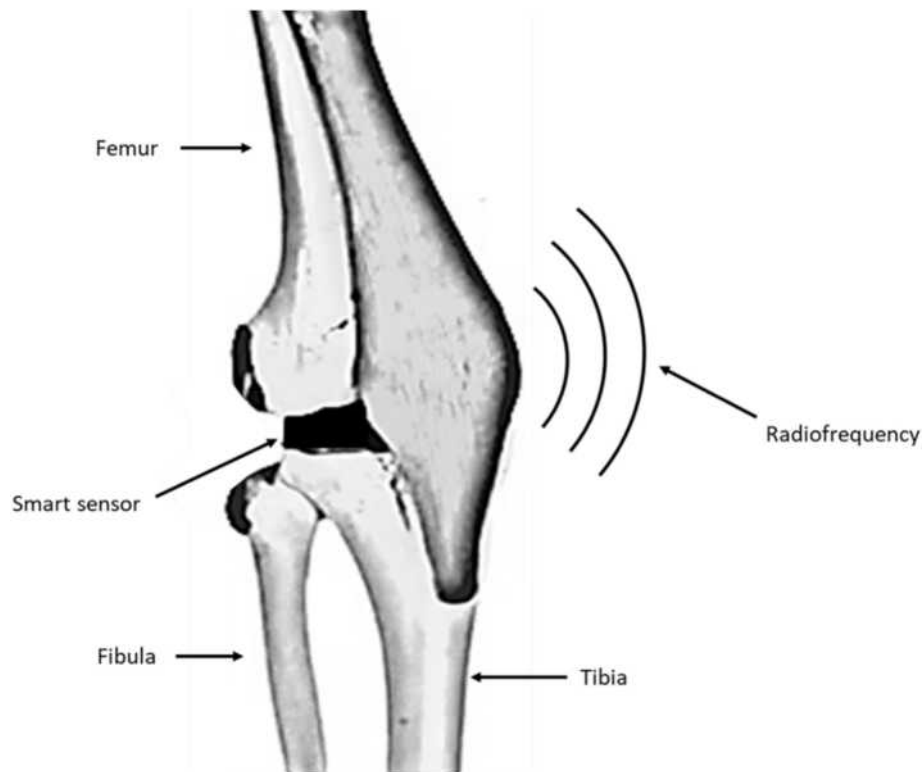


Fig. 3. Schematic presentation of orthopaedic non-invasive smart implant sensor technology.

required by the body without delay, implanting electronic devices with radiating signals inside the human body is still a concern for scientists and medical experts [54]. Many experts have been skeptical about biosensors and nanosensor device implants due to the probability of damages they may cause to the human body [55]. Every human body reacts differently to smart medical devices implanted inside it. The risk of non-invasive smart implants and the signals emitted by them damaging the soft and delicate tissues and organs is persistent [9]. There is a fair chance that the body will consider a non-invasive smart implant as a foreign body and generate pathogenic cells to develop strong immunity.

Such repeated actions of the body may weaken the immune system and probably cause harm to the body.

e. Health data security and privacy risks

Non-invasive smart implants collect patients' health status that may expose detailed and personal health information. This can impose catastrophic repercussions on the security and privacy of the person's health data [56]. To ensure security and privacy, preventive and security measures and standards should be considered in non-invasive smart implants.

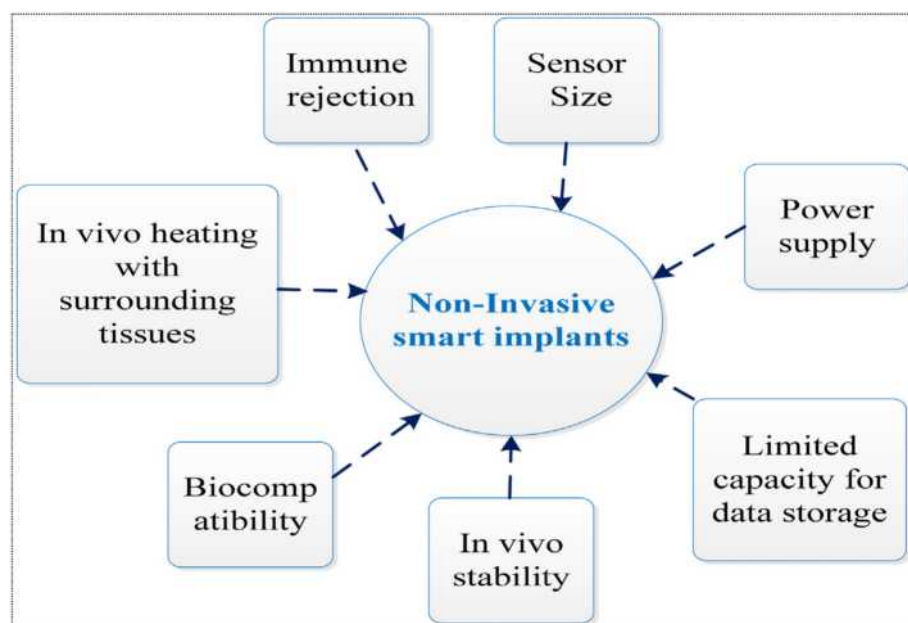


Fig. 4. Non-invasive smart implants clinical challenges.

f. Non-invasive smart implants clinical challenges

Although research on non-invasive smart implants is nascent, there are lots of difficulties in their practical implementation, as shown in Fig. 4. For example, how to use them, where to put and when to use them. These are difficult questions in their practical implementation despite the process being the least invasive. Some authors have proposed that non-invasive smart implants can be implanted in subcutaneous tissue or superficial mucosa with non-invasive technique, rather than in other deeper body areas like the aorta or another vascular system, the heart, where more invasive techniques are required [19]. In addition, with the use of subcutaneous biosensors, immune response may disrupt the sensing power by generating fibrous tissue between the sensor and the body. The formation of the tissue matrix may lead to the failure of the devices. Some non-invasive smart implants are affected by the issue of size. Ideally, smart implants need to be as small as possible and take as little space as possible once inside the body. This is even more important where extra space might be needed for the sensor itself. For example, although cochlear implants and pacemakers have been used routinely for some time, they are continually undergoing size reduction to make them as portable as possible. Although small-sized implants are ideal, there are some negative connotations attached to their use. One of the downsides of having very small smart implants is that small implants have limited capacity for data storage leading to inadequate disease surveillance [57]. As their name suggests, non-invasive smart implants should be non-invasive and minimally invasive so that body trauma is kept at a minimum during implantation. The non-invasiveness of smart implants is, however, inevitably, positively correlated to their sizes. Another challenge associated with smart implant technology is the reaction of the body towards these implants. To reduce the chances of the body rejecting the implants as foreign, and consequently rejecting them, the implants should be biocompatible and as much as possible not interfere with natural biochemical processes within the body. Non-invasive smart implants mustn't cause infections within the body, which can lead to immune rejection. For example, implants used for treating heart disease need constant power supply [58] but the consumption of power should be as minimal as possible to prevent the heating of surrounding tissues as well as to elongate battery life. On the other hand, orthopedic smart implants can be usually short-lived depending on the bodyweight that they have to sustain [59].

The further development of non-invasive smart implants requires more research for more knowledge gain especially in critical areas of the human body such as the nervous and the skeletal systems. Further advancements in smart implant technology can also be made through the development of implantable devices that can fully homogenize with living human tissues and organs for optimal functional abilities. Implantable devices need to be able to transfer physiological data to the exterior of the body efficiently and robustly at very little cost. The *in vivo* stability of non-invasive smart implants is also important to their optimal functioning without affecting the homeostasis of surrounding bodily tissues.

7. Recommendations for future use of non-invasive smart implants in healthcare

Despite many opportunities presented by smart implants, sensors and emerging digital technologies in healthcare, some hurdles might hinder their successful adoption and use, as shown in this paper. To minimize the impact of such hurdles, we recommend the following:

- (a) **Provision of robust security and privacy measures** - all smart implants, sensor and emerging digital health technologies and apps must provide robust security mechanisms to ensure patient data security [60]. Whether at rest or in transit, patient data must be secured using robust encryption algorithms and de-identified before traversing networks. Security is always a concern in

digital health and ensuring robustly secure smart implants can help convince more people to use the technology.

- (b) **Stakeholder involvement** - the creators of smart technologies and the interfacing apps must involve stakeholders in designing the solutions for them to be people-centric and increase the chances of successful adoption and utilization [61–63]. Involving stakeholders in the design of non-invasive smart implants presents an opportunity that can improve the device functionalities and potentially influence the adoption and utilization of these devices [64,65].
- (c) **Regulatory framework** - healthcare is a regulated sector that requires all technological interventions to meet minimum expectations. However, regulatory frameworks are always behind the pace of technological innovations [66], with policymakers struggling to keep up with the pace [61]. Instead of individual countries having their regulatory frameworks, we recommend a generic global framework spearheaded by the World Health Organization. This will help accelerate innovations while meeting the minimum required regulations.
- (d) **Standardization and synchronization of protocols** - these are important to enable compatibility and interoperability [67] to prevent data silos. Interoperability helps ensure data sharing among health care providers, which may result in better care for patients by enabling access to patient care history. Moreover, this may help provide compatible datasets for health research in order to improve patient care and health delivery. Moreover, standardization and synchronization of protocols helps minimize the challenges involved in interfacing different systems, thus, reducing the time taken to deploy digital health care systems. It is possible to interface different systems through standardization, making it easier for health experts to share patient data for care purposes.
- (e) **Zero-rating of digital health apps** - the data collected by smart implants and other sensors as well as digital apps need to be communicated and sent through networks. Accessing such networks requires data connections, the cost of which some people may not afford [68]. We, therefore, recommend that governments and internet service providers provide free access to the network for such apps and technologies.

8. Conclusion

Non-invasive smart implants offer a great opportunity to solve some of the most debilitating diseases of our times such as chronic heart diseases. The integration of implant technology and biosensors literally affords the direct monitoring of the implants and the tissues that surrounds them inside the living body. As our study has shown, different implants for different diseases face different and sometimes unique challenges. One commonality though is the fact that the use of biosensors reduces the available space *in vivo* for the implant as these sensors also take up space. One of the most common implant surgeries is dental implant technology. Because of this, it is also very expensive. This may be seen as a disadvantage to the financially challenged and poorer communities. Some implantation surgeries such as cardiovascular implant surgery are disadvantaged by lack of scientific knowhow. The spinal cord, for example, is a very complicated structure that to this day is continually being studied. This therefore makes implantation of non-invasive devices on the spinal cord a very complicated affair. Despite the challenges associated with non-invasive smart sensor-integrated implants, our study reported the benefits that this technology brings such as early disease detection which afford early disease prevention as well as other benefits such as enhanced management of health information. We recommend robust legislation that will regulate non-invasive implant technology as well as patient data protection parameters that will ascertain the safety of the technology. Finally, we recommend stakeholder involvement in non-invasive smart implant technology as a way of growing the field and

expanding medical gain. Future work could focus on strategies to encourage, promote or enhance the adoption of non-invasive sensors in clinical practice in Sub-Saharan Africa since the region is lagging in terms of virtual healthcare [69,70].

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

List of abbreviations

COVID-19 Coronavirus disease 2019

MoO₃ Molybdenum trioxide

THA Total hip arthroplasty

TKA Total knee arthroplasty

SARS-CoV-2 Severe acute respiratory syndrome coronavirus 2

UHMWPE Ultra-high molecular weight polyethylene

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