Towards the Development of a Low-Cost Artificial Pancreas: A Solution to Type-1 Diabetes in Sub-Saharan Africa

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Abstract: In Type-1 Diabetes (T1-D), proper health monitoring can lead to better disease mitigation; thus, reducing the number of face-to-face visits by patients. This can be achieved through insulin replacement therapy using either multiple daily injections or continuous insulin infusion through an artificial pancreas (AP). AP is more accurate and effective than injections, assisting patients in better managing their glucose levels. Conventional AP mimics the operation of the human pancreas by delivering small doses of short-acting insulin continuously, or bolus insulin in response to meals or certain activities. The vital requirement for smart AP is the presence of systems that detect glucose levels in real time using minimally invasive and low-power devices. This can be achieved using power-efficient on-site monitoring devices. Therefore, this review presents the state-of-the-art in the development of intelligent and power-efficient glucagon and insulin delivery systems for type 1 diabetes (T1-D) management as well as the future perspectives on the development of smart AP systems. Emphasis is placed on its practicability for use in sub-Saharan Africa.
Keywords: Artificial Pancreas; Closed-Loop Control; Dual-Hormone; Power Harvesting; and Fuzzy Logic Controller.

Introduction

Diabetes has a significant impact on the African continent due to epidemiological factors and healthcare economic difficulties. Urbanization is a major factor contributing to the rise in diabetes prevalence in Africa. The high presence of public transportation in urban communities has led to the reduction of physical activities such as trekking and lifting of goods. On the contrary, people in the local communities still engage in such activities due to poor transportation network (Gill *et al.*, 2009). A growing number of individuals are migrating from rural to urban regions, particularly in Sub-Saharan Africa. This migration is intimately connected to a transition in lifestyle from a relatively healthy traditional pattern to an urban situation of increased food quantity and decreased quality, low levels of exercise, smoking, and greater alcohol availability (Gill *et al.*, 2009). According to International Diabetes Federation estimates from 2009 (Marchetti *et al.*, 2015), the number of adults with diabetes in the globe would increase by 54% by 2030; that is, from 284 million in 2010 to 438 million in 2030. Sub-Saharan Africa is expected to grow by 98 percent in the same period; that is, from 121 million in 2010 to 239 million in 2030 (Mbanya *et al.*, 2010).

This rapid and significant epidemiological change is causing an increase in the prevalence of diabetes and hypertension. As well as quantitative issues, Diabetes epidemiology in Africa is also marked by a number of qualitative differences. Economic factors continue to be a significant impediment to adequate diabetes care delivery in Africa. In resource-constrained countries, insulin, in particular, is a relatively expensive drug (Mbanya *et al.*, 2010). In terms of diet, one of the ideas supported by rural/urban comparisons of African people is that with urban exposure, the traditional diet is abandoned in favor of a Western diet characterized by declines in carbohydrate, fiber and increases in fat. Traditional food is linked to a lower prevalence of degenerative disorders, but the Western diet is linked to an increased prevalence (Pretorius and Sliwa, 2011).

Diabetes is a disease that stems from atypical levels of insulin in the body, due to either a malfunction of the pancreas resulting in it not producing enough insulin or the cells in the body not utilizing it satisfactorily (Organization and others, 2003). Insulin is a hormone that regulates the level of glucose by allowing cells to absorb it from the bloodstream to obtain energy or store it for future use. In Type-1 Diabetes (T1-D), proper health monitoring can lead to better disease mitigation; thus, reducing the number of face-to-face visits by patients. This can be achieved through insulin replacement therapy using either multiple daily injections or continuous insulin infusion through an artificial pancreas (AP), also called an insulin pump. An AP is a closed-loop system that automates all insulin/glucagon delivery and requires minimal user inputs for meals, exercise, snacks, and sleep. It mimics the operation of the human pancreas by delivering small doses of short-acting insulin continuously, or bolus insulin in response to meals or certain activities. However, there are a number of problems associated with insulin pumps: errors of insulin infusion, insulin stability issues, infusion site problems, user error, or a combination of these (Heinemann *et al.*, 2015). A number of these challenges can be addressed using adaptive (or smart) insulin delivery systems.

As shown in Fig. 1, a closed-loop or adaptive insulin delivery system consists of a number of modules with different functionalities: sensor, pump and feedback control modules. The sensed signal of the AP system is usually the blood glucose concentration; however, other physiological parameters can also be monitored or controlled. The sensor system contains at least one continuous glucose monitoring (CGM) sensor, as well as other physiological parameters including heart rate, accelerometer and pulse oximetry (Chakrabarty *et al.*, 2019). The manipulated variable (MV) is either the insulin or glucagon infusion dose at each time instant. The feedback control module processes the blood glucose and relevant physiological measurements through a pre-processing unit. This is used by the controller to calculate the insulin or glucagon doses required at discrete time instants. So far, closed-loop systems have been limited by the speed of insulin action, lag time in CGM sensing and delays in gastric absorption of food (Weinzimer *et al.*, 2008). As such, robust feedback algorithms that predict glucose and its rate of change are necessary to achieve safe and effective glucose regulation for people with type-1 diabetes (T1-D).

In Nigeria, Improving the availability, accessibility, affordability, and quality of health care is one of the pillars of the Economic Recovery and Growth Plan (ERGP). Having a power-efficient AP could provide a sustainable solution for T1-D in sub-Saharan Africa as well as reduce mortality rates. Generally, diabetes is one of the most expensive global diseases to manage for patients in the poorest regions of the world, like sub-Saharan Africa. Hence, promoting technology for T1-D management and other electroceuticals is essential. Due to challenges in terms of access and availability of electricity in sub-Saharan Africa, this review will also explore the use of low-power pumps using energy harvesting techniques, with a view to providing recommendations. The rest of this paper is organized as follows: Section 2 reviews the fundamentals of artificial pancreas. Section 3 describes the development towards low-cost AP systems. Section 4 presents the future perspectives and finally section 5 concludes the paper.

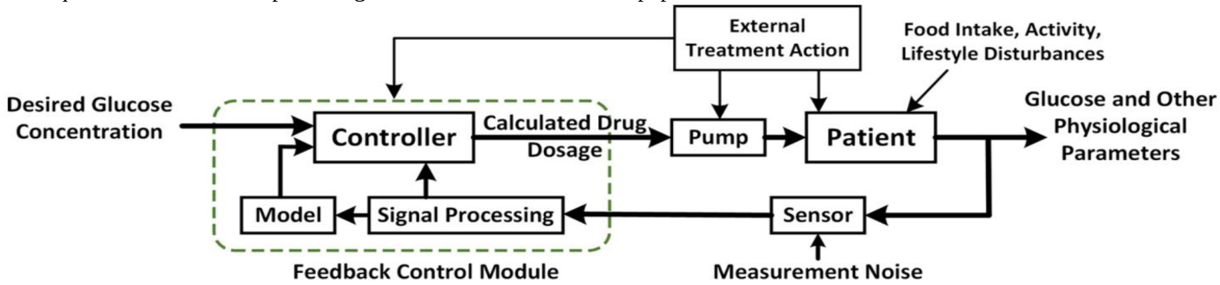

Fig. 1: Block Diagram of an Artificial Pancreas System (Shi, Deshpande, Dassau, & Doyle III, 2019).

ARTIFICIAL PANCREAS FUNDAMENTALS

Patients with T1-D require insulin replacement therapy using either multiple daily injections or continuous insulin infusion through an insulin pump (also known as continuous subcutaneous insulin infusion (CSII)) (Taylor and Forlenza, 2020). While insulin pumps provide real-time information of glucose level and trends, as well as ways of customizing insulin delivery; nevertheless, only a handful of patients achieve the proper glucose levels. By the adoption of smart (adaptive) insulin delivery systems, efficient blood glucose control can be achieved. Two configurations of insulin delivery are currently in use: delivery of insulin alone, and the delivery of both insulin and glucagon (Haidar, 2016). Insulin needs varies significantly between patients. Basal insulin needs can be as low as 0.2 units/hour in young children and as high as 2.0 units/hour in obese adults. Also, insulin needs vary across patients as a result of insulin-sensitivity of patients. As such, several control algorithms have been proposed including proportional integral-derivative, model predictive control and fuzzy control to overcome this (Haidar, 2016). A number of automated and machine learning techniques have also been used to manage the required level of insulin in the body (Kropff *et al.*, 2015). The use of learning algorithms provided an overall improvement in diabetic patients' quality of life. A long-term randomized controlled home trial of people aged 12 – 25 years with T1-D showed a higher potential to improving glycemic and quality of life outcomes in closed-loop systems than standard care (De Bock *et al.*, 2018). Using closed-loop insulin delivery, it has been demonstrated that short and long-term complications associated with diabetes management can be minimized (Lal *et al.*, 2019). The algorithms are expected to control hyperglycemia, while reducing the risks of hypoglycemia. The following sections provide more detail on the sub-systems required to implement a low-cost artificial pancreas.

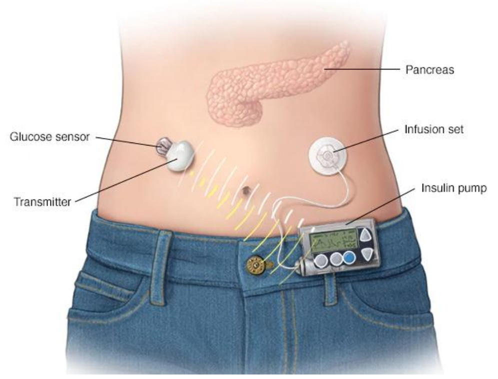

Fig. 2: Wirelessly Operated Smart Artificial Pancreas.

Glucose Measurement Techniques

If the degree of glucose in the blood stays extremely low or exceptionally high for significant stretches of time, it could cause hypoglycemia or hyperglycemia, respectively, leading to severe medical conditions, including stroke, kidney failure, tissue damage, blindness, heart disease, among other ailments, which could lead to death if left untreated (Jungheim and Koschinsky, 2002). Insufficient creation of insulin in the pancreas prompts T1-D, portrayed by the abrupt drop of glucose levels – hypoglycemia. Also, ineffectual utilization of insulin prompts type 2 diabetes (T2-D), which is described by significant levels of glucose. Regular glucose monitoring in diabetic patients is necessary for the rest of their lives as both conditions do not have a cure. The issue of consistently checking the blood glucose for most diabetic individuals is not pleasant. The advancement of non-invasive tools for glucose estimation would speak to a groundbreaking element for a significant number of patients around the World thus, enabling them to keep track of their glucose levels and getting speedy treatment when necessary (Villena *et al.*, 2019).

Conventional methods for glucose measurement and management could be roughly classified into two: laboratory-based and home-based. Various laboratory techniques were investigated in (Delost, 2014; Villena *et al.*, 2019) were either enzymatic-amperometric or hexokinase approach was employed with scope restricted to plasma such as blood and serum within certain glucose range measurement. Laboratory techniques are highly accurate and sensitive; however, their main disadvantages stem from the inherent invasiveness as blood samples need be taken from patients. Other challenges include the need for trained laboratory personnel and extended waiting periods of time (Villena *et al.*, 2019). For home monitoring, the techniques can either be continuous or non-continuous monitoring as reported in (Schultz, 2009; Wadwa *et al.*, 2009; Nardacci *et al.*, 2010; Patton and Clements, 2012; Rebel *et al.*, 2012; Ekhlaspour *et al.*, 2017; Chakrabarty *et al.*, 2019). Despite their good reliability and accuracy, there is consistently the inconveniences of pain and distress brought about by standard finger-pricking a few times daily, and the costs of obtaining test strips. The invasiveness, temporal resolution, distress on patients and sample contamination are some of the factors that militate on the monitoring technique (Villena *et al.*, 2019).

The non-invasive technologies can be classified based on different forms such as level of invasiveness: minimally-invasive (MI) and non-invasive (NI). Or, based on signal detected: optical, thermal, and electrical. Various researches under the non-invasive methods include surface Plasmon resonance (Szmacinski and Lakowicz, 1995; Barone *et al*, 2005; Srivastava *et al.*, 2012; Zeng *et al.*, 2014; Chen et al., 2018), optical polarimetry (Rawer *et al.*, 2004; Malik and Coté, 2010), OCT-optical coherence tomography (Fercher *et al.*, 2003; Lan *et al.*, 2017), time of flight/terahertz time domain spectroscopy (Alarousu *et al.*, 2004; Cherkasova *et al.*, 2009; Withayachumnankul and Naftaly, 2014; Gusev *et al.*, 2017; Torii *et al.*, 2017), thermal spectroscopy (Klonoff, 1997; Malchoff *et al.*, 2002) among many others. A comprehensive review can be found in (Villena *et al.*, 2019).

Adaptive Controller

An adaptive controller is any control system with adjustable inputs and outputs and a mechanism for altering them. It contains two loops, a control loop and a parameter adjustment loop (Katigari *et al.*, 2017). The development of automated 'intelligent' systems has several advantages, because they are more reliable than manual interventions and are less prone to fatigue and miscomputations. Recently, a proposition was given on diabetic neuropathy for diagnosing diabetic sickness utilizing a fuzzy expert system, where the results obtained showed a system accuracy of 93% (Katigari *et al.*, 2017). Fuzzy logic (FL) makes computations by investigating about changing degrees between absolutes. FL works using adaptive controllers, which utilize an improved type of human 'fuzzy' thinking. An excellent review of medical applications on fuzzy logic inference system can be found in (Thukral and Bal, 2019). The choice of fuzzy control was driven by their ability to provide computationally efficient and robust decision making. This is necessary because implantable systems have certain resource constraints, like power and size. Consequently, by using FLC, as more knowledge on T1-D for each patient is gained, the fuzzy rules could be updated, which provides an adaptable control scheme. With the inclusion of power harvesting techniques in the AP systems, there may be less need for battery replacements for implantable systems. Energy harvesting is essential because the economic costs associated with AP is dominated by battery replacement costs.

Fuzzy controller

Fuzzy logic control has received a lot of interest from both the academic and industry communities over the last decade. Many people have put in a lot of time and effort into theoretical study as well as implementation strategies for fuzzy logic controllers. Fuzzy logic control has been proposed as an alternate method to traditional control approaches for complicated control systems to date (Ma *et al.*, 1998). Fuzzy logic control is one of the most useful ways for designing a controller based on qualitative understanding of a system. Fuzzy logic control approaches are used to collect human knowledge and skill while also dealing with uncertainties in the control process date (Ma *et al.*, 1998). With the advancement of neural networks and fuzzy systems, it is now known that a system's qualitative knowledge can be expressed in a nonlinear functional form. Some model-based fuzzy control system design methodologies have emerged in the fuzzy control field on the basis of this concept date (Ma *et al.*, 1998). Therefore, using FLC, as new knowledge about T1-D for each patient is gathered, the fuzzy rules may be changed, resulting in an adaptable control system.

Hormone Actuation and Delivery System

Most hormone actuation and delivery systems subcutaneous delivery of glucagon and insulin. The major trend is to use microelectromechanical systems (MEMS)-based piezoelectric actuators as the pumping diaphragm for insulin infusion.

Energy Harvesting

There are three suitable sources of energy from human movement for energy harvesting devices which come in the form of mechanical (kinetic) energy. They are acceleration pulse upon heel strike (between shoe and ground), the acceleration due to the leg swing during walking and the force that acts upon the shoe due to the weight of the person (Niu *et al.*, 2004; Ylli *et al.*, 2015). Furthermore, there are three typical ways to convert the harvested mechanical energy from these sources into electrical energy: electromagnetic, electrostatic (also known as triboelectric) and piezoelectric.

Piezoelectric energy harvesting has been used in applications that require high voltage, high energy density, high capacitance, and little mechanical damping (Roundy *et al.*, 2004; Boisseau *et al.*, 2012; Khalid *et al.*, 2019). Techniques used to increase efficiency for piezoelectric energy harvesting include: non-linearity (Cao *et al.*, 2015; Wang *et al.*, 2017), double pendulum system (Lin *et al.*, 2017) and frequency up conversion (Pillatsch, Yeatman and Holmes, 2014). Advantages of piezoelectric energy harvesting include the following (Erturk and Inman, 2011; Wu *et al.*, 2016).

- High power density – does not need an external voltage source.
- Good scalability.
- Versatile shapes.
- Ease of application and fabrication – can be fabricated both at macro- and micro-scales.

Piezoelectric harvesters can either be active or passive (Covaci and Gontean, 2020). Passive harvesters deliver energy from the body with no excitation or powering a device, while active harvesters require powering devices. Energy can be harnessed from the body through breathing, pulse, and body heat (Ren *et al.*, 2007; Invernizzi *et al.*, 2016). Thermal energy as a critical energy source can be changed over into power using either thermoelectric generators (TEGs), or pyroelectric generators (PEGs) (Bell, 2008; Lou, Li, Wang, & Shen, 2010). Several works proposed power generation from lead zirconate titanate (PZT) PEG films (Yang *et al.*, 2012; Potnuru and Tadesse, 2014; Kim *et al.*, 2015). Among the passive harvesters, thermal energy harvesters use body heat and do not depend on body movement. They can work uninterruptedly 24 hours daily. Also, they can provide more dependable electrical energy than active harvesters at similar output power (Zhou *et al.*, 2018).

IoT Interface for AP

One of the most prominent areas of IoT is health and medical care. This has the potential of converting conventional healthcare from being hospital-centric to patient-centric (Pang, 2013). A secured IoT based datalogging and remote interface is required to connect the glucose monitoring system, insulin pump and energy harvesting. The universal and customized administrations of human healthcare IoT (H2IoT) redesigned the medical care from career-centric to patient-centric (Liu *et al.*, 2011; Plaza *et al.*, 2011; Klasnja and Pratt, 2012).

Human embedded sensors on patients collect information remotely by diagnosing the medical condition and administering the required medication/therapy. A wide range of IoT systems have been used to diagnose patient's conditions (Pasluosta *et al.*, 2015; Chang *et al.*, 2016). The work in (Yuehong *et al.*, 2016) utilized different remote physiological sensors which read and sends the physiological elements of an individual by means of a wireless medium. Wearable sensors and remote health monitoring systems enhanced the reachability of physicians in urban areas to rural areas for health care access. In terms of IoT based glucose management system, a temperature sensing module was used in conjunction with non-invasive blood glucose sensing module for enabling real-time monitoring of blood glucose level (Istepanian *et al.*, 2011).

Several IoT systems have been developed including in health monitoring and control (Ashton and others, 2009), patient-based identification (Jara *et al.*, 2010), and universal health care (Doukas and Maglogiannis, 2012; Schreier, 2014). In addition, IoT-based remote management frameworks have been developed (Sundmaeker *et al.*, 2010; Bui and Zorzi, 2011). Remote management framework builds the efficiency of tackling the patient accessibility issues (Swift *et al.*, 2002; Chan *et al.*, 2006; Caudill *et al.*, 2011). A non-specific IoT-based medical system was also proposed for monitoring the glucose level in (Guan, 2013). Therefore, A state-of-the-art AP system suitable for sub-Saharan Africa could be implemented with IoT systems such as embedded processors, phones and computers, while ensuring effective operation.

TOWARDS A LOW-COST AP

This section will focus more on the major areas that are necessary in driving development towards low-cost AP systems by incorporating more intelligence in the system and harnessing background energy.

Computational Intelligence for Biomedical Systems

This takes advantage of artificial intelligence and adaptive control methods to provide computationally efficient and robust solutions to challenging problems in the control and estimation of parameters for biomedical circuits and systems (Begg, Lai and Palaniswami, 2007).

Intelligent Glucose Monitoring and Adaptive Controller

This implements estimation of glucose level. In addition, it could incorporate low-cost controllers like fuzzy logic control, which relies on mapping between discrete state estimates to determine control signal to insulin pump. The choice of fuzzy control is driven by its ability to provide computationally efficient control that can be implemented on systems which are reliable, low power and low-cost. In this approach, glucose estimation and drug delivery components of the artificial pancreas could be linked by an embedded fuzzy controller based on PID or MPC (Lal *et al.*, 2019). Various metrics for control objectives to be considered will include bringing blood glucose to a target level, keeping it in a zone, or the total time in euglycemic range. By combining continuous glucose sensing with insulin pump technology running on fuzzy logic rules, a development of a closed-loop artificial pancreas in the form of either an external or an implantable sensor is proposed. This artificial pancreas could provide feedback to an external or implantable pump as shown in Fig. 3.

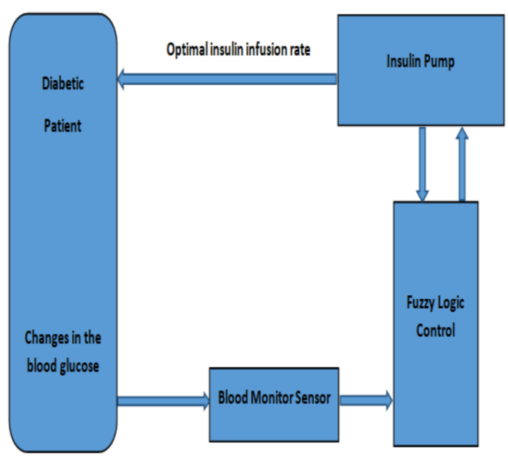

Fig. 3: A Closed-loop Artificial Pancreas System.

Smart Insulin Pumps

MEMS-based piezoelectric actuator as the pumping diaphragm for insulin infusion are the most efficient drug delivery system. The integrated drug delivery system consists of drug reservoir, micropumps, valves, sensors, signal transducer (conditioning) and an (adaptive) controller. A simplified block diagram of a drug delivery system is shown in Fig. 4.

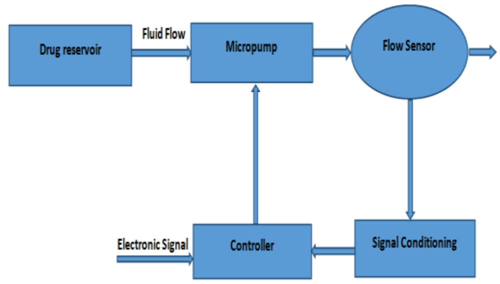

Fig. 4: Schematic Diagram of the Integrated Drug Delivery System.

Micropump as an essential component of the drug delivery system shown in Fig. 4 would transfer the drug in fluid format from the drug reservoir to the body (tissue or blood vessel) with accuracy and precision. The proposed MEMS-based piezoelectric micropump would consist of a piezoelectric disk attached on a diaphragm, a pumping chamber and valves actuated by the deformation of the piezoelectric materials.

Secured Datalogger and Remote Interface for Disease Tracking

To effectively track disease progression and changes in glucose level, a data logging system is required to guide clinicians on future therapy. The overall system can be broken down into four main parts: sensing, control, display and server stages. The display and server stages will allow for secured datalogging and remote interface. Fig. 5 shows a general block diagram of the system. The sensing unit of Fig. 5 involving glucose detection, insulin pump and energy harvesting. The system will be used by trained physicians to predict or forecast impending health danger and prevent possible probability of patient's criticality.

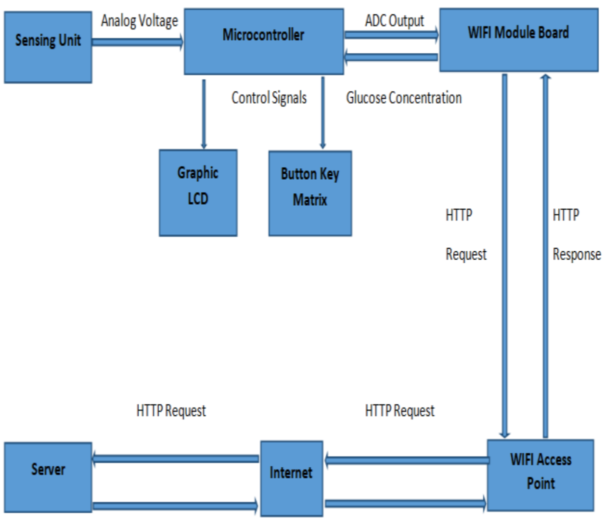

Fig. 5: Block Diagram of the Datalogging & Remote interface of an AP System.

Energy Harvesting for Implantable Electronics

This explores the harvesting of electromagnetic, kinetic, and thermal energies from human body motion and environmental sources for implantable devices (Kiziroglou and Yeatman, 2012). There are several techniques for harnessing energy from bodily sources including human motion and thermal body gradients. Below are the three main techniques for harnessing energy from human motion:

1. Force-driven harvester in the form of bending of piezoelectric materials attached to the shoe sole, both ceramics and polymer-based could be employed (Abdal and Leong, 2017). A generator using a lever and mechanical gears will be used to translate the downward motion of the foot into a rotational motion.
2. Acceleration driven harvester in the form of a piezoelectric macro scale prototype where a heavy cylindrical mass is set into motion when the foot is lifted to form an angle with the ground (Safaei *et al.*, 2019). Magnets attached to piezoelectric beams should snap towards this mass when it comes into range and vibrate freely at their resonance frequency, when released.
3. Swing motion harvester where a multi-coil configuration is used in conjunction with concentrically placed magnets separated by ferromagnetic steel spacers (Safaei *et al.*, 2019). The system model will follow real-world acceleration data and a differential equation based on a number of different forces acting upon the moving magnet such as the external acceleration input due to the foot motion, the forces due to air compression, friction forces and the electrical damping force

Secondly, energy harvesting using thermal body gradients is a common technique (Kiziroglou and Yeatman, 2012). Heat exchange with the environment takes place through the skin interface. Different parts of the human body are geometrically modeled as concentric cylinders with each layer representing bone, muscle, fat, dermis, and epidermis (Fig. 6).

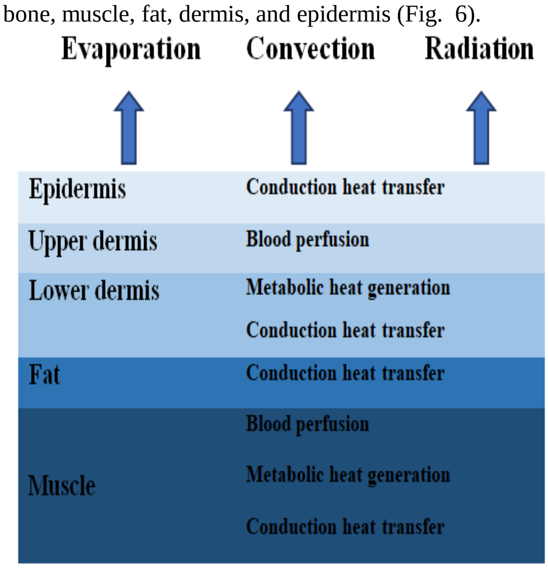

Fig. 6: Modelling Various Aspects of the Human Body

Different mathematical models such as Newton's law of cooling and Stephen-Boltzmann Law are used to model the convective heat, radiative and evaporative thermal energies shown in Fig. 6. A proposed block diagram for harvesting kinetic energy of human body movement is shown in Fig. 7.

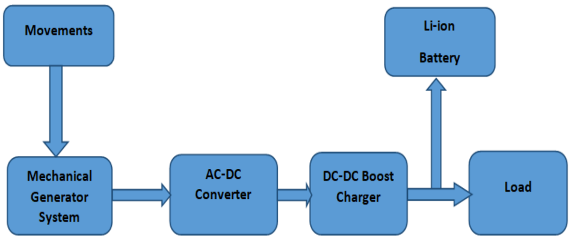

Fig. 7: Proposed Energy Harvester for Human Body Movements

The model of Fig. 7 contains a transducer, kinetic energy harvester, optimized converters (AC-DC/DC-DC) and energy storage element. Alternatively, thermal energy conversion from electrical energy using TEG devices could be adopted.

FUTURE PERSPECTIVES

Issues Militating the Development of Smart AP Systems

Based on 2019 figures, about 463 million people suffer from diabetes out of which 19 million living in sub-Saharan Africa (Saeedi *et al.*, 2020). Yet, only 0.1 % of those requiring insulin have access to AP systems. AP is more accurate and effective than injections, helping patients better manage glucose levels. In diabetes, proper health monitoring can lead to better disease mitigation; thus, reducing the number of face-to-face visits by patients. For proper management of blood glucose, feedback algorithms that maintain it within the euglycemic safe range of 70 – 180 mg/dL are required. This prevents postprandial hyperglycemia with limited patient intervention as well as reduce hypoglycemic events (Doyle III *et al.*, 2014). However, designing robust AP systems for this may be difficult for a number of reasons. Primarily, the unequal risks associated with hypoglycemia and hyperglycemia makes setting constraints difficult. Hypoglycemia can be life-threatening while hyperglycemia can cause severe health challenges and could lead to death in the long term – hyperglycemia is the normal condition of T1-D patients. Secondly, the slow response due to the electrochemical sensors for glucose monitoring coupled with the lag associated with insulin delivery– deadtime and dynamical lag associated with insulin pharmacokinetics – can result in over-delivery or under-delivery of insulin. These, together with the narrow therapeutic window of insulin, imposes limitations on insulin actuation.

Furthermore, the insulin-glucose metabolic dynamics is a highly non-linear process, which is susceptible to lifestyle, environmental factors, and disease progression. This makes obtaining an accurate mapping between glucose and insulin requirements very difficult. In addition, there are security and privacy issues with wirelessly transmitting sensed data for glucose regulation. To overcome some of these challenges, it will be important to have studies that answer the following questions.

- How can multi-signal and implantable predictive algorithms for monitoring glucose levels be implemented?
- Which control strategies are most effective for modulating insulin delivery, such that they are robust to noise, behaviorally induced changes in glucose requirements, environmental factors, disease progression and other electrical or metabolic disturbance sources in patients?
- Which insulin infusion strategies are the most feasible for on-site and implantable hardware implementation?

- How can disease progression be monitored remotely?
- What power harvesting techniques can be used for implantable electronics?

This can be achieved using power-efficient on-site monitoring devices; which monitor glucose levels at the site of insulin infusion. The main advantage of this approach over wirelessly transmitting measured glucose levels is the low-power and throughput requirements; because, health monitoring systems are required to be operational for long periods of time.

Expected Impact of Smart AP Systems

The major requirement for smart AP systems is to detect glucose levels in real-time using minimally invasive and low-power devices. In sub-Saharan Africa, the short-term goal of developing smart AP systems is to realize a fully implantable closed-loop system for insulin delivery, which leads to better treatment options for patients, as well as improve their quality of life. The advantages of this system include improved efficacy of therapy; more targeted drug delivery; less insulin may be required to treat T1-D; thus, reducing the cost of insulin (McCall and Farhy, 2013). Also, there may be reduction of possible side effects. In the long-term, technical competence of researchers and stakeholders in the area of biomedical circuits and systems in Nigeria and sub-Saharan Africa will improve. This will enhance the development and application of innovative technologies, which could result in spin-off companies. The development of an AP system requires a team that includes clinicians, engineers and computer scientists. This will advance the formation of multidisciplinary research teams as well as the development of pedagogical tools for biomedical engineering and allied disciplines. Below are some possible impacts of nurturing AP systems:

- ***Patients:*** smart AP has the ability to adjust insulin dosage to changes in patient's lifestyle and environmental factors. In addition, the adoption of energy harvesting will reduce the need for frequent battery replacements in areas with limited power sources. Both of this will ensure that there are improvements in patient's quality of life (Shah *et al.*, 2016).
- ***Clinicians:*** the device could store large amounts of insulin-glucose data that can be used for monitoring and tracking of disease progression. This could improve the understanding of the disease by clinicians; thus, improving the safety, efficiency and quality of therapy.
- ***Entrepreneurs:*** the development and adoption of novel technologies could lead to the proliferation and growth of startups in the area of medical technologies in sub-Saharan Africa (Drincic *et al.*, 2016). The availability and accessibility of this technology in sub-Saharan Africa could drive unit costs down as manufacturers achieve economies of scale. Low-cost devices can translate to better market penetration, which will result in better management of T1-D in sub-Saharan Africa.
- ***Researchers, Educators and Academic Mentorship*:** this will enhance competencies of researchers and young academics in the area of biomedical circuits and systems. Nurturing and supporting local talents in Africa is imperative. The more we are challenged, the more experience and competence we gain for future projects.

Domestication and Deployment of Smart AP Systems

To fully domesticate and deploy smart AP systems, prototypes will need to be developed and tested. As technology development progresses, there are growing concerns in society as to what this technological development entails. In using these technologies, ethics, security, safety and privacy are growing areas of research and recommending possible ways of managing these challenges is one of the cornerstones of technology deployment and domestication. Technology development consists of the following five elements (five M's):

- Materials and resources (including energy)
- Machines and equipment
- Manpower (engineers and skilled workers)
- Management (technology management and management technology)
- Markets for technology and its products

Modern technology must have all of these elements to function properly. Money and information are also indispensable components in each of the elements. As such, we could develop a strategy, where low-cost computational intelligence is incorporated in AP systems. Lessons learnt from incorporating low-cost intelligence would be used to guide the incorporation of energy harvesting.

To attain complete self-reliance in technology, none of these five stages should be skipped. For sub-Saharan Africa as a late starter in these technologies, we have the advantage of economizing time, money, and energy at each stage of development; since we will learn from the experiences of other countries. Constant reliance on foreign technology is undesirable as was evident during the COVID-19 pandemic. As such, developing a national/local capability in biomedical systems is important because foreign technologies often lack uniformity in their standardization and may not be customized to our local needs. The success of this would depend on the research and development capability of technological stakeholders in the country.

Conclusion

The fundamentals and importance of low-cost AP towards better management of glucose levels for T1-D patients were discussed in this paper, with more emphasis on the implant ability and use in sub-Saharan Africa. Incorporating energy harvesting systems makes the system more economical and it reduces the challenges in terms of access and availability of electricity in sub-Saharan Africa. Also, incorporating artificial intelligence for glucose monitoring which provide computationally efficient and robust solutions to the control and estimation of parameters. For proper management of insulin and glucose levels in T1-D patients in sub-Saharan Africa, there is need to attain complete self-reliance in the development of cost-efficient and intelligent AP systems. As such, promoting technology for T1-D management and other electroceuticals is essential towards improving access to healthcare in sub-Saharan Africa.

References

Abdal, A. M. and Leong, K. S. (2017) 'Piezoelectric pre-stressed bending mechanism for impact-driven energy harvester', in *IOP Conference Series: Materials Science and Engineering*, p. 12037.

Alarousu, E. *et al.* (2004) 'Noninvasive glucose sensing in scattering media using OCT, PAS, and TOF techniques', in *Saratov Fall Meeting 2003: Optical Technologies in Biophysics and Medicine V*, pp. 33–41.

Ashton, K. and others (2009) 'That "internet of things" thing', *RFID journal*, 22(7), pp. 97–114.

Barone, P. W., Parker, R. S. and Strano, M. S. (2005) 'In vivo fluorescence detection of glucose using a single-walled carbon nanotube optical sensor: design, fluorophore properties, advantages, and disadvantages', *Analytical chemistry*, 77(23), pp. 7556–7562.

Begg, R., Lai, D. T. H. and Palaniswami, M. (2007) *Computational intelligence in biomedical engineering*. CRC Press.

De Bock, M. *et al.* (2018) 'Effect of 6 months hybrid closed-loop insulin delivery in young people with type 1 diabetes: a randomised controlled trial protocol', *BMJ open*, 8(8), p. e020275.

Boisseau, S., Despesse, G. and Seddik, B. A. (2012) 'Electrostatic conversion for vibration energy harvesting', *Small-scale energy harvesting*, 5.

Bui, N. and Zorzi, M. (2011) 'Health care applications: a solution based on the internet of things', in *Proceedings of the 4th international symposium on applied sciences in biomedical and communication technologies*, pp. 1–5.

Cao, J. *et al.* (2015) 'Nonlinear time-varying potential bistable energy harvesting from human motion', *Applied Physics Letters*, 107(14), p. 143904.

Caudill, T. S. *et al.* (2011) 'Commentary: Health care reform and primary care: training physicians for tomorrow's challenges', *Academic Medicine*, 86(2), pp. 158–160.

Chakrabarty, A. *et al.* (2019) 'Getting IoT-ready: The face of next generation artificial pancreas systems', in *The Artificial Pancreas*. Elsevier, pp. 29–57.

Chan, L., Hart, L. G. and Goodman, D. C. (2006) 'Geographic access to health care for rural Medicare beneficiaries', *The Journal of Rural Health*, 22(2), pp. 140–146.

Chang, S.-H. *et al.* (2016) 'A context-aware, interactive M-health system for diabetics', *IT professional*, 18(3), pp. 14–22.

Chen, L., Hwang, E. and Zhang, J. (2018) 'Fluorescent nanobiosensors for sensing glucose', *Sensors*, 18(5), p. 1440.

Cherkasova, O. P. *et al.* (2009) 'Terahertz spectroscopy of biological molecules', *Radiophysics and Quantum Electronics*, 52(7), pp. 518–523.

Covaci, C. and Gontean, A. (2020) 'Piezoelectric energy harvesting solutions: A review', *Sensors*, 20(12), p. 3512.

Delost, M. (2014) 'Blood gas and critical care analyte analysis' , *Equipment for Respiratory Care. Jones and Bartlett Publishers, Inc*.

Doukas, C. and Maglogiannis, I. (2012) 'Bringing IoT and cloud computing towards pervasive healthcare', in *2012 Sixth International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing*, pp. 922–926.

Doyle III, F. J. *et al.* (2014) 'Closed-loop artificial pancreas systems: engineering the algorithms', *Diabetes care*, 37(5), pp. 1191–1197.

Drincic, A. *et al.* (2016) 'Evidence-based mobile medical applications in diabetes', *Endocrinology and Metabolism Clinics*, 45(4), pp. 943–965.

Ekhlaspour, L. *et al.* (2017) 'Comparative accuracy of 17 point-of-care glucose meters', *Journal of diabetes science and technology*, 11(3), pp. 558–566.

Erturk, A. and Inman, D. J. (2011) *Piezoelectric energy harvesting*. John Wiley \& Sons.

Fercher, A. F. *et al.* (2003) 'Optical coherence tomography-principles and applications', *Reports on progress in physics*, 66(2), p. 239.

Gill, G. V *et al.* (2009) 'A sub-Saharan African perspective of diabetes', *Diabetologia*, 52(1), pp. 8–16.

Guan, Z. J. (2013) 'Somatic data blood glucose collection transmission device for Internet of Things', *Chinese Patent*, 202(838), p. 653.

Gusev, S. I. *et al.* (2017) 'Application of terahertz pulsed spectroscopy for the development of non-invasive glucose method', in *2017 Progress In Electromagnetics Research Symposium-Spring (PIERS)*, pp. 3229–3232.

Haidar, A. (2016) 'The artificial pancreas: How closed-loop control is revolutionizing diabetes', *IEEE Control Systems Magazine*, 36(5), pp. 28–47.

Heinemann, L. *et al.* (2015) 'Insulin pump risks and benefits: a clinical appraisal of pump safety standards, adverse event reporting, and research needs: a joint statement of the European Association for the Study of Diabetes and the American Diabetes Association Diabetes Technology Working Group', *Diabetes care*, 38(4), pp. 716–722.

Invernizzi, F. *et al.* (2016) 'Energy harvesting from human motion: materials and techniques', *Chemical Society Reviews*, 45(20), pp. 5455–5473.

Istepanian, R. S. H. *et al.* (2011) 'The potential of Internet of m-health Things "m-IoT" for non-invasive glucose level sensing', in *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 5264–5266.

Jara, A. J. *et al.* (2010) 'Drugs interaction checker based on IoT', in *2010 Internet of Things (IOT)*, pp. 1–8.

Jungheim, K. and Koschinsky, T. (2002) 'Glucose monitoring at the arm: risky delays of hypoglycemia and hyperglycemia detection', *Diabetes care*, 25(6), pp. 956–960.

Katigari, M. R. *et al.* (2017) 'Fuzzy expert system for diagnosing diabetic neuropathy', *World journal of diabetes*, 8(2), p. 80.

Khalid, S. *et al.* (2019) 'A review of human-powered energy harvesting for smart electronics: recent progress and challenges', *International Journal of Precision Engineering and Manufacturing-Green Technology*, 6(4), pp. 821–851.

Kim, M.-S. *et al.* (2015) 'Modeling of a honeycomb-shaped pyroelectric energy harvester for human body heat harvesting', *Smart Materials and Structures*, 24(6), p. 65032.

Kiziroglou, M. E. and Yeatman, E. M. (2012) 'Materials and techniques for energy harvesting', in *Functional Materials for Sustainable Energy Applications*. Elsevier, pp. 541–572.

Klasnja, P. and Pratt, W. (2012) 'Healthcare in the pocket: mapping the space of mobile-phone health interventions', *Journal of biomedical informatics*, 45(1), pp. 184–198.

Klonoff, D. C. (1997) 'Noninvasive blood glucose monitoring', *Diabetes care*, 20(3), pp. 433–437.

Kropff, J. *et al.* (2015) '2 month evening and night closed-loop glucose control in patients with type 1 diabetes under free-living conditions: a randomised crossover trial', *The lancet Diabetes \& endocrinology*, 3(12), pp. 939–947.

Lal, R. A. *et al.* (2019) 'Realizing a closed-loop (artificial pancreas) system for the treatment of type 1 diabetes', *Endocrine reviews*, 40(6), pp. 1521–1546.

Lan, Y. T. *et al.* (2017) 'Noninvasive monitoring of blood glucose concentration in diabetic patients with optical coherence tomography', *Laser Physics Letters*, 14(3), p. 35603.

Lin, J. *et al.* (2017) 'A rotational wearable energy harvester for human motion', in *2017 IEEE 17th International conference on nanotechnology (IEEE-NANO)*, pp. 22–25.

Liu, C. *et al.* (2011) 'Status and trends of mobile-health applications for iOS devices: A developer's perspective', *Journal of Systems and Software*, 84(11), pp. 2022–2033.

Ma, X.-J., Sun, Z.-Q. and He, Y.-Y. (1998) 'Analysis and design of fuzzy controller and fuzzy observer', *IEEE Transactions on fuzzy systems*, 6(1), pp. 41–51.

Malchoff, C. D. *et al.* (2002) 'A novel noninvasive blood glucose monitor', *diabetes care*, 25(12), pp. 2268–2275.

Malik, B. H. and Coté, G. L. (2010) 'Real-time, closed-loop dual-wavelength optical polarimetry for glucose monitoring', *Journal of biomedical optics*, 15(1), p. 17002.

Marchetti, P. *et al.* (2015) 'Diabetes mellitus: epidemiology, pathophysiology, and treatment', *Oxford Textbook of Transplant Anaesthesia and Critical Care*, p. 165.

Mbanya, J. C. N. *et al.* (2010) 'Diabetes in sub-saharan africa', *The lancet*, 375(9733), pp. 2254–2266.

McCall, A. L. and Farhy, L. S. (2013) 'Treating type 1 diabetes: from strategies for insulin delivery to dual hormonal control', *Minerva endocrinologica*, 38(2), p. 145.

Nardacci, E. A., Bode, B. W. and Hirsch, I. B. (2010) 'Individualizing Care for the Many', *The Diabetes educator*, 36(1_suppl), pp. 4S--19S.

Niu, P. *et al.* (2004) 'Evaluation of motions and actuation methods for biomechanical energy harvesting', in *2004 IEEE 35th annual power electronics specialists conference (IEEE Cat. No. 04CH37551)*, pp. 2100–2106.

Organization, W. H. and others (2003) *Screening for type 2 diabetes: report of a World Health Organization and International Diabetes Federation meeting*.

Pang, Z. (2013) *Technologies and Architectures of the Internet-of-Things (IoT) for Health and Well-being*. KTH Royal Institute of Technology.

Pasluosta, C. F. *et al.* (2015) 'An emerging era in the management of

Parkinson's disease: wearable technologies and the internet of things', *IEEE journal of biomedical and health informatics*, 19(6), pp. 1873–1881.

Patton, S. R. and Clements, M. A. (2012) 'Continuous glucose monitoring versus self-monitoring of blood glucose in children with type 1 diabetes-are there pros and cons for both?', *US endocrinology*, 8(1), p. 27.

Pillatsch, P., Yeatman, E. M. and Holmes, A. S. (2014) 'A piezoelectric frequency up-converting energy harvester with rotating proof mass for human body applications', *Sensors and Actuators A: Physical*, 206, pp. 178–185.

Plaza, I. *et al.* (2011) 'Mobile applications in an aging society: Status and trends', *Journal of Systems and Software*, 84(11), pp. 1977–1988.

Potnuru, A. and Tadesse, Y. (2014) 'Characterization of pyroelectric materials for energy harvesting from human body', *Integrated Ferroelectrics*, 150(1), pp. 23–50.

Pretorius, S. and Sliwa, K. (2011) 'Perspectives and perceptions on the consumption of a healthy diet in Soweto, an urban African community in South Africa: a healthy diet in Soweto', *SA Heart*, 8(3), pp. 178–183.

Rawer, R., Stork, W. and Kreiner, C. F. (2004) 'Non-invasive polarimetric measurement of glucose concentration in the anterior chamber of the eye', *Graefe's Archive for Clinical and Experimental Ophthalmology*, 242(12), pp. 1017–1023.

Rebel, A., Rice, M. A. and Fahy, B. G. (2012) 'The accuracy of point-of-care glucose measurements', *Journal of diabetes science and technology*, 6(2), pp. 396–411.

Ren, K. *et al.* (2007) 'An active energy harvesting scheme with an electroactive polymer', *Applied physics letters*, 91(13), p. 132910.

Roundy, S., Wright, P. K. and Rabaey, J. M. (2004) 'Piezoelectric Converter Test Results', in *Energy Scavenging for Wireless Sensor Networks*. Springer, pp. 87–114.

Saeedi, P. *et al.* (2020) 'Mortality attributable to diabetes in 20--79 years old adults, 2019 estimates: Results from the International Diabetes Federation Diabetes Atlas', *Diabetes research and clinical practice*, 162, p. 108086.

Safaei, M., Sodano, H. A. and Anton, S. R. (2019) 'A review of energy harvesting using piezoelectric materials: state-of-the-art a decade later (2008--2018)', *Smart Materials and Structures*, 28(11), p. 113001.

Schreier, G. (2014) 'The internet of things for personalized health', *Stud Health Technol Inform*, 200, pp. 22–31.

Schultz, D. G. (2009) 'FDA public health notification: potentially fatal errors with GDH-PQQ* glucose monitoring technology', *US Department of Health and Human Services*.

Shah, R. B. *et al.* (2016) 'Insulin delivery methods: Past, present and future', *International journal of pharmaceutical investigation*, 6(1), p. 1.

Srivastava, S. K., Verma, R. and Gupta, B. D. (2012) 'Surface plasmon resonance based fiber optic glucose biosensor', in *Third Asia Pacific Optical Sensors Conference*, pp. 451–456.

Sundmaeker, H. *et al.* (2010) 'Vision and challenges for realising the Internet of Things', *Cluster of European research projects on the internet of things, European Commision*, 3(3), pp. 34–36.

Swift, E. K. and others (2002) 'Guidance for the national healthcare disparities report'.

Szmacinski, H. and Lakowicz, J. R. (1995) 'Fluorescence lifetime-based sensing and imaging', *Sensors and Actuators B: Chemical*, 29(1–3), pp. 16–24.

Taylor, K. A. and Forlenza, G. P. (2020) 'Use of Machine Learning and Hybrid Closed Loop Insulin Delivery at Diabetes Camps', *Diabetes Technology \& Therapeutics*, 22(7), pp. 535–537.

Thukral, S. and Bal, J. S. (2019) 'Medical applications on fuzzy logic inference system: a review', *International Journal of Advanced Networking and Applications*, 10(4), pp. 3944–3950.

Torii, T. *et al.* (2017) 'Measurements of glucose concentration in aqueous solutions using reflected THz radiation for applications to a novel sub-THz radiation non-invasive blood sugar measurement method', *Digital health*, 3, p. 2055207617729534.

Villena Gonzales, W., Mobashsher, A. T. and Abbosh, A. (2019) 'The progress of glucose monitoring—A review of invasive to minimally and non-invasive techniques, devices and sensors', *Sensors*, 19(4), p. 800.

Wadwa, R. P. *et al.* (2009) 'Continuous glucose monitoring in youth with type 1 diabetes', *Diabetes Technology \& Therapeutics*, 11(S1), p. S--83.

Wang, W. *et al.* (2017) 'Optimum resistance analysis and experimental verification of nonlinear piezoelectric energy harvesting from human motions', *Energy*, 118, pp. 221–230.

Weinzimer, S. A. *et al.* (2008) 'Fully automated closed-loop insulin delivery versus semiautomated hybrid control in pediatric patients with type 1 diabetes using an artificial pancreas', *Diabetes care*, 31(5), pp. 934–939.

Withayachumnankul, W. and Naftaly, M. (2014) 'Fundamentals of measurement in terahertz time-domain spectroscopy', *Journal of Infrared, Millimeter, and Terahertz Waves*, 35(8), pp. 610–637.

Wu, L. *et al.* (2016) 'A self-powered and optimal SSHI circuit integrated with an active rectifier for piezoelectric energy harvesting', *IEEE Transactions on Circuits and Systems I: Regular Papers*, 64(3), pp. 537–549.

Yang, Y. *et al.* (2012) 'Pyroelectric nanogenerators for driving wireless sensors', *Nano letters*, 12(12), pp. 6408–6413.

Ylli, K. *et al.* (2015) 'Energy harvesting from human motion: exploiting swing and shock excitations', *Smart Materials and Structures*, 24(2), p. 25029.

Yuehong, Y. I. N. *et al.* (2016) 'The internet of things in healthcare: An overview', *Journal of Industrial Information Integration*, 1, pp. 3–13.

Zeng, S. *et al.* (2014) 'Nanomaterials enhanced surface plasmon resonance for biological and chemical sensing applications', *Chemical Society Reviews*, 43(10), pp. 3426–3452.

Zhou, M. *et al.* (2018) 'A review on heat and mechanical energy harvesting from human--Principles, prototypes and perspectives', *Renewable and Sustainable Energy Reviews*, 82, pp. 3582–3609.