Pressure Injury Prevention: A Survey

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***Abstract*—Pressure injuries are caused by prolonged pressure to an area of the body, which can result in open wounds that descend to the bone. Pressure injuries should not occur in healthcare settings and yet they still affect 2.5 million patients in the U.S and have an impact on quality of life. Pressure injuries come at a cost of $11 billion in the U.S. and 90% of pressure injuries are a secondary condition. In this work we survey the literature on preventative techniques to address pressure injures, which we classify into two categories: Active Prevention Strategies and Sensor-Based Risk-Factor Monitoring. Within each category of techniques we discuss the literature and assess each class of strategies based on its commercial availability, results of clinical trials when available, the ability for the strategy to save time for healthcare staff, and whether the technique can be tuned to an individual. Based on our findings the most promising current solutions supplementary to nursing guidelines are Electrical Stimulation, Pressure Monitoring, and Inertial Measurement Unit Monitoring. We also find a need for a clinical software system that can easily integrate with custom sensors, use custom analysis algorithms, and provide visual feedback to the healthcare staff a necessity.**

I. Introduction

PRESSURE injuries, recently standardized from the term pressure ulcers or decubitus ulcers by the National Pressure Ulcer Advisory Panel [1], are classified colloquially as a “never event”, meaning they should never occur in health care settings and yet in the U.S. there are over 2.5 million patients affected every year at a cost of $11 billion [2]. More than 90% of pressure injuries are a secondary condition, meaning the patient was being treated for a different condition when the pressure injury formed [3].

Biomechanically pressure injuries are caused by prolonged pressure to an area of the body. Through a combination of prolonged closure of capillaries and lymphatic vessels, ischemia, reperfusion, and tissue deformation the affected tissue dies [4] [5] [6]. Typically this occurs at the bony prominences, such as the sacrum or heels in a patient lying down. The result is an open wound that descends to the bone, which must be further treated to avoid infection.

We use the term pressure throughout this paper to refer to pressure applied to the body at any angle in order to account for both pressure and shear force. We do so as the majority of the work surveyed does not make a clear differentiation of the effect of pressure versus shear. We find that this simplifies the discussion while still accurately presenting the material.

Pressure injuries have an impact on quality of life as they cause severe pain, treatments increase discomfort and pain, and impact the social life of the patient [7] [8]. Pressure injuries are generally developed while being treated for a different condition, but the resulting pressure injury can affect treatment options [8].

Pressure injuries do not form in the healthy patient, but are common in patients with low mobility as these patients cannot reposition themselves. Garcia-Fernandez et al. [9] identified 83 risk factors used in various pressure injury scales. Of these 83 risk factors an expert panel determined 23 risk dimensions, meaning multiple risk factors were interrelated and could be grouped together. Of the 23 risk dimensions the five that were considered critical in order of importance are mobility, exposure to moisture/incontinence, mental state/level of consciousness, nutrition/diet, and activity. In other words, patients who are at risk for pressure injuries are already suffering from previous conditions and in addition have to cope with a pressure injury.

In an effort to reduce pressure injury occurrence in the U.S. Medicaid and Medicare Services decided to no longer reimburse “never events” [10]. Through improved and more focused nursing care guidelines the prevalence, a benchmarking metric of hospital-acquired pressure injuries in the U.S. were reduced from 6.2% in 2006 to 3.1% in 2015 [11]. The end goal is to have a prevalence of 0% or very close to it, although as we will discuss in Section III this is somewhat debated. Also important to note is that although there was a 1% drop in prevalence from 2008 to 2009 when reimbursements stopped the prevalence in 2013, 2014, and 2015 respectively was 3.2%, 3.4%, and 3.1% [11], which may indicate that nursing guidelines and established nursing interventions alone may not be enough to bring down pressure injury below a 3% prevalence.

This work is a literature survey of work on preventing pressure injuries from 2010 to present. Although not the main focus we present some of the fundamental problems in the pressure injury prevention field and some of the landmark pressure injury studies derived from the literature. We do so in order to give context to the work surveyed, but also to make this work a standalone snapshot of how and why the research to prevent pressure injuries has led to the current prevention strategies. Our expertise is in the space of Computer Engineering and Bioengineering and therefore we offer a unique perspective on current and future technological solutions.

There are three recent literature surveys that we are aware of that have some overlap with this work [12] [13] [6]. In 2015 a literature survey on software solutions to prevent pressure injuries was presented [12]. This work identifies approaches that monitor sensor information that can be used to prevent pressure injuries. We also cover pressure injury prevention strategies that monitor sensor information, but in addition we cover new literature up until July of 2018, which includes several randomized controlled trials conducted after the previous work was published, we cover new sensor monitoring strategies not covered in the previous work, we cover pressure injury prevention strategies that are not sensor-based, and we created a taxonomy of all strategies that provides insight into which strategies are the most promising currently and for the future.

In [13] papers were reviewed from 2013-2016 with a focus on different types of skin ulcers and the effectiveness of current technologies that are used in healthcare to prevent pressure injuries. Our work also covers technologies that are currently used in healthcare, although we do not cover different types of skin ulcers, we focus only on pressure injuries. But, in addition we examine technologies that are not currently being used in healthcare and we classify all pressure injury prevention strategies using a taxonomy we created to provide insight into which strategies are the most promising currently and for the future.

The most recent literature survey that has some overlap with our own was published in 2018 [6]. This work explores current technologies that can assess the skin integrity of a patient with a focus on the prevention of diabetic foot ulcers. We also cover technologies that assess the skin integrity of a patient, although there are some technologies, such as Magnetic Resonance Imaging (MRI) and Finite Element Modeling, that we do not cover. But, in addition we cover technologies that can prevent pressure injuries without assessing the skin integrity of a patient that are effective at reducing pressure injuries, such as Inertial Measurement Unit Monitoring and

Electrical Stimulation. In addition we also created a taxonomy of all strategies to provide insight into the most promising currently researched strategies and the most promising for the future.

Our work starts with a brief history of modern pressure injury prevention in Section II to give context to the current practices and research of today. This leads into a discussion on how pressure injuries are currently classified and how that classification relates to "never events" as well as the current research on whether all pressure injuries are preventable in Section III. We then discuss the current research on the biomechanics or pathophysiology of pressure injuries in Section IV to give the reader an understanding of how and why pressure injuries form. We then introduce our taxonomy on pressure injury prevention strategies in Section V that classifies each technique that we cover based on the commercial availability, clinical results of prevention, time savings, and ability to tune the technique to an individual. In Section VI we cover Active Prevention Strategies, a technique that requires active work from healthcare staff to prevent pressure injuries, such as nursing guidelines and nutrition. We will discuss why we consider each technique an Active Prevention Strategy in each subsection. In Section VII we cover Sensor-Based Risk-Factor Monitoring Strategies, a technique that gathers data about a patient and can present it to healthcare staff when needed, to prevent pressure injuries, such as Pressure and Temperature Monitoring. In Section VIII we discuss the most promising current prevention strategies and what we see as the most promising future work based on the work presented. We present our conclusion in Section IX.

II. Brief History

The first recorded instances of pressure injuries date back thousands of years to ancient Egypt [5]. In the early 19th century Jean-Martin Charcot studied pressure injuries, but attributed their formation to an impaired nervous system [14] [5]. In the early 20th century Dr. William Browning established a pressure injury prevention plan, which resembles the treatment plans of today [14].

In the literature of today the two hour turning of high risk pressure injury patients is commonly mentioned [15] [16] [17] [18] [19]. It is believed that the standard two hour turning cycle used today was established during World War II as this is the time it takes on average to turn 32 patients in a nursing unit for war victims [20].

Around this same time Groth [21] performed animal studies that showed increasing the amount of pressure and the time of pressure increased the damage to the muscle fibers and capillaries [22]. Husain in the 1950s [23] continued this work and established that $100mmHg$ applied for two hours to the legs of rats and guinea pigs caused permanent damage to the skeletal muscle. Kosiak in the 1960s [24] [25] established that it is more complicated than a simple threshold and instead it is a pressure-time threshold, e.g., a high pressure of $190mmHg$ for a very short time period will not form a pressure injury, but a low pressure of $70mmHg$ for a long period of time will form a pressure injury. The first human study was conducted by Reswick and Rogers [26] in the 1970s and they established a $300mmHg \times hour$ threshold.

The interface pressure, the pressure of the patient against a surface, such as a mattress or chair, became the first well known way to monitor pressure injuries using sensors. But, given these first studies were conducted in the 1940s to 1970s the technology of the time was only able to use pressure sensors to generate a generic pressure-time curve that could be applied to any patient.

The most established pressure-time curve based on human studies is the Reswick and Rogers Pressure-Time Curve [26], as depicted in Figure 1. Reswick and Rogers conducted a study of the interface pressure at the bony prominences in the 1970s using a singular pressure device to study a wide range of patients. The pressure-time curve they found creates a threshold of $300mmHg \times hour$, e.g. if a patient is immobile for one hour the continuous pressure should be less than $300mmHg$, if a patient is immobile for two hours the continuous pressure should be less than $150mmHg$. Reswick and Rogers created the pressure-time curve as a guideline and it was not meant to be used quantitatively.

At the extremes of the time scale the Reswick and Rogers Pressure-Time Curve has received criticism as it "allows" for pressure high enough to rupture organs for very short periods of time and predicts pressure injuries to form during twelve-hour long operations that do not occur [22]. In addition as we will describe in Section IV pressure injuries start their formation in deep tissue and interface pressure is the pressure between the body and mattress or chair. Studies have shown that the deep tissue pressure on the bony prominence cannot always be reduced significantly with cushioning that reduces interface pressure [4].

Another problem with interface pressure is that the same amount of interface pressure does not correspond to the same amount of deep tissue pressure [22]. A study on the seated patient studied six subjects using Magnetic Resonance Images and Finite Element Analysis to determine the amount of strain on the tissue under the ischial turbosities (sit bones) and it was confirmed that the tissue closest to the ischial turbosities had the highest strain, but the amount of strain varied by patient based on the shape of the ischial turbosities and the amount of muscle and fat [27], i.e. a seated patient with a lower interface pressure may be more at risk than a patient with a higher interface pressure.

To date it is established that a pressure-time curve cannot be used to prevent pressure injuries for every patient. To combat this many approaches have been tested and evaluated, some of which take an active role from health care staff such as nursing guidelines or Support Surfaces, as will be discussed in Section VI. Other approaches are based on sensor monitoring such as continuous Pressure Monitoring or even measuring the physical WiFi channel as will be discussed in Section VII. The various approaches are based on the current understanding of the biomechanics of pressure injury formation, which we will discuss in Section IV, but first we will introduce the reader to the classification of pressure injuries and how they relate to the term "never event" as well as the current research on whether all pressure injuries are preventable.

III. Never Events And Unavoidable Pressure Injuries

Although colloquially known as "never events", the term used by the National Quality Forum (NQF) in their reports are "serious reportable events" [28]. For consistency we will mention this here, but will continue to use the term "never event".

Never events range from operating on the wrong patient or a serious injury from a patient disappearance [28]. It is often cited that pressure injuries are never events, and in fact we do so in our Introduction, but it is actually only Stage 3, Stage 4, and Unstageable pressure injuries that occur after admission to a healthcare setting that are considered never events.

There are various staging classifications of pressure injuries, one of the more popular in the United States is created by the NPUAP. As a reference the 2016 pressure injury staging from the NPUAP is summarized [1]:

Stage 1	Non-blanchable erythema of intact skin
Stage 2	Partial-thickness skin loss with exposed dermis
Stage 3	Full-thickness skin loss
Stage 4	Full-thickness skin and tissue loss
Unstageable	Obscured full-thickness skin and tissue loss
Deep Tissue	Persistent non-blanchable deep red, maroon, or purple discoloration

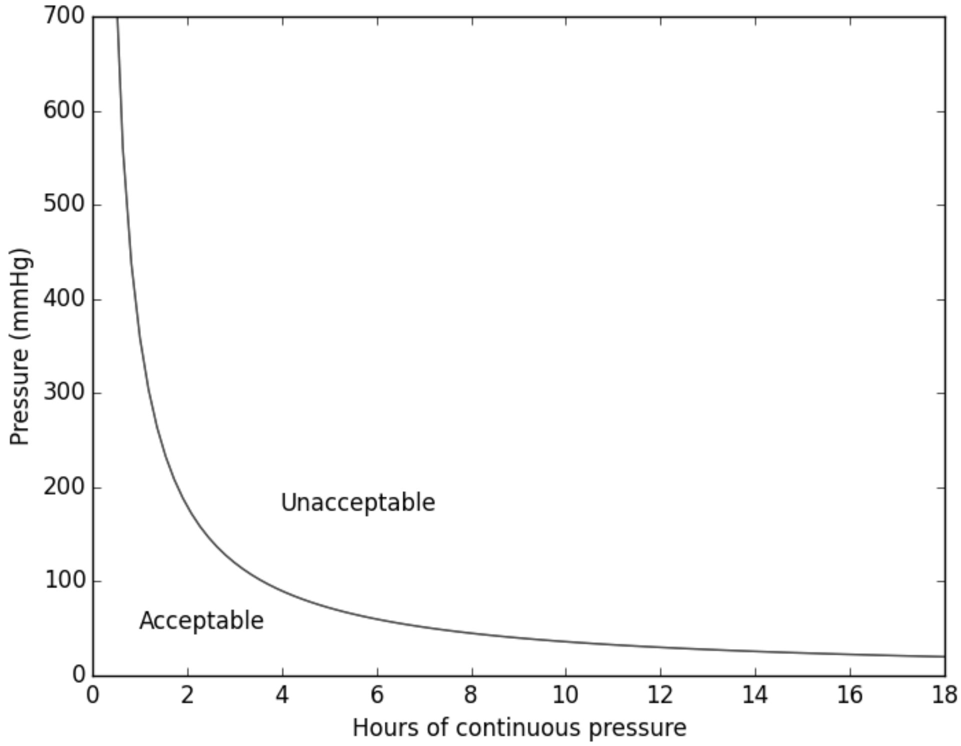


Fig. 1: Reswick and Rogers Pressure-Time Curve

The staging, as stated by the NPUAP, is not meant to be used as a progression, but instead as different types of pressure injuries that can occur. In particular Stage 1 injures are somewhat controversial and are addressed by Berlowitz and Brienza [4] as they note that Stage 1 pressure injuries can occur because of incontinence and do not have any deep tissue injury component.

The NQF mentions in their report [28] that Deep Tissue staged pressure injuries were considered as being never events, but this "would amount to reporting an unconfirmed suspicion."

Some pressure injuries are unavoidable as based on a consensus study by Edsberg et al. [29]. An unavoidable pressure injury is defined as a pressure injury that forms when all preventative measures were correctly assessed and implemented [29]. Although not definitive the study points out that in some cases preventative measures cannot be implemented because the patient is at critically high risk or the prevention would interfere with other conditions of the patient. This is important to consider as this indicates that there may be some percentage of pressure injuries that can never be prevented, but this percentage is not yet determined.

IV. Biomechanics

As their name implies pressure is the main cause of pressure injuries. From the literature there are five supported reasons why pressure cause their namesake injury. In no particular order they are [4] [5] [6]:

1) Closure of capillaries causing ischemia to the surrounding tissue.
2) Under high pressure, the closure of large vessels causing thrombosis.
3) The accumulation of substances produced by inflammation in response to blood being reintroduced into an ischemic region, known as a reperfusion injury.
4) An accumulation of metabolic waste products from an impaired lymphatic system caused by pressure closing the lymphatic vessels.
5) The pressure deformation of tissue cells.

As continual pressure is applied to the body, almost exclusively from a bed or chair, a combination of the above occur. Internally the pressure has the greatest effect at the bony prominences. This effect was studied analytically and in vivo to reveal that the greatest stress was in the muscle layer next to the bone [4]. This type of injury is called a deep tissue injury.

If we go back and look at the Stage 1 classification of pressure injuries, it is only the skin that is visibly diagnosed. Stage 1 injuries can be a result of deep tissue and studies have shown this, but also can be a Superficial Injury, which is not a result from pressure [4]. Superficial Injuries can be caused by urinary and fecal incontinence, the friction of dragging a patient to be turned, or shear forces tearing blood vessels and will typically occur at the bony prominences [4]. Although Superficial Injuries occur at similar locations and in similar patients these injuries are not a result of pressure and it is argued that they should not be considered a pressure injury as they do not result from pressure [4] [9]. This is an important note as studies will frequently use Stage 1 to indicate the presence of a pressure injury, but this has to be taken with a grain of salt unless otherwise noted, it was most likely not verified to be from deep tissue damage.

Another factor that is often recognized is that an increase in skin temperature correlates to the formation of pressure injuries, but it is believed that this may be from the effects of temperature on ischemia [4]. As temperature rises the metabolic rate increases, which increases the demand of oxygen. In an ischemic region, such as a pressure injury, this increased demand of oxygen will accelerate the damage to the ischemic region. But, to confuse the issue an animal study found that deep tissue injuries happened more frequently at lower temperatures [4], not higher temperatures. The increase or decrease in temperature may be an indicator of pressure injuries, but it is unclear at this time how to use such data.

V. Taxonomy Of Pressure Injury Prevention

The current work on preventing pressure injuries fit into one of two categories: Active Prevention Strategies or Sensor-Based Risk-Factor Monitoring. Active Prevention Strategies are approaches that take an active role from a healthcare staff to implement, such as nursing guidelines or nutrition. Sensor-Based Risk-Factor Monitoring are strategies that have the potential to operate without any intervention of healthcare staff, such as Pressure and Temperature Monitoring.

To evaluate the effectiveness/applicability of these techniques in the prevention of pressure injuries we created a rubric as follows:

Commercial Availability	Is the application commercially available or is it a prototype/idea?
Clinical Trials	Are there clinical trials? And if so do they support the effectiveness?
Time Savings	Does the application save time for the healthcare staff?
Tuned To Individual	Is the application general or based on the individual patient? For example repositioning a patient every two hours is a general guideline and is not tuned to the individual, whereas Pressure Monitoring is measuring the actual pressure from the patient and decisions can be made based on the individual.

Each category is scored as $\uparrow$, ... , $\downarrow$, or NA . A $\uparrow$ indicates that the rubric category is satisfied, e.g., the application is commercially available. A ... indicates that it is either mixed or cannot be determined, e.g., a prototype was made. A $\downarrow$ indicates that the reverse is shown instead, e.g., the application is not available and is just an idea. NA means it is not applicable, this is specifically for the clinical trials category, if a pressure injury prevention strategy is not clinically tested it will be marked NA . A $\uparrow$ in all categories indicates a desirable quality. Each application will be discussed in more detail in the following sections, Table I is provided as an overview of the gaps in the field and what is to be discussed.

VI. Active Prevention Strategies

We refer to the following prevention strategies as Active Prevention Strategies as they take an active role of a healthcare staff. We present nursing guidelines in Section VI-A as a reference for all other techniques as nursing guidelines are part of current care and will be needed regardless of any other additional techniques. Nursing guidelines are an Active Prevention Strategy almost by definition as they are guidelines that the healthcare staff must actively follow. In Section VI-B we will discuss Support Surfaces, mattresses or overlays that actively or passively reduce the interface pressure between the patient and surface. Although the original intent of Support Surfaces may have been to be a set it and forget it technique it is generally accepted now that this is not the case, which we will discuss. We classify Support Surfaces as an Active Prevention Strategy as the general use case is a supplemental tool for healthcare staff. There is no feedback given by the surface and therefore the healthcare staff must rely on their own knowledge and experience on using the surface appropriately. In Section VI-C we will discuss the latest research on nutrition as a way to prevent and increase healing of pressure injuries. Nutrition is an Active Prevention Strategy as the nutrients for the patient must be managed by a healthcare staff. In Section VI-D we will discuss the latest research on Electrical Stimulation, a technique of contracting muscles using electric current, which we categorize as an Active Prevention Strategy as a healthcare staff must actively apply electrodes and verify that muscles are being contracted on every application. In each subsection we will discuss the latest research as well as the taxonomy criteria as it applies to the respective technique: commercial availability, clinical trials, time savings, and whether the technique is tuned to the individual.

A. *Nursing Guidelines/Interventions*

Nursing guidelines on preventing pressure injuries are published by the National Pressure Ulcer Advisory Panel (NPUAP) and the European Pressure Ulcer Advisory Panel(EPUAP) [30]. The “Quick Reference Guide” cited here is a 75 page document with extensive information that includes recommendations for care with the level of clinical evidence that supports each recommendation. A selection from the guidelines include risk factors, risk factor assessment, preventative skin care, emerging therapies, nutrition, repositioning, Support Surfaces, medical device related pressure injuries, wound cleaning, pain assessment, wound dressings, special populations, and implementing guidelines. The former is only a selection of the guidelines and each section is covered in detail.

Nursing guidelines/interventions are extensive and because it is not the main focus of our survey we have chosen to discuss a subset of proposed approaches in the literature namely: reposition frequency, risk assessment scales, and how following interventions are correlated with pressure injury incidence reduction/prevention.

It is often noted that two hours is the standard of care repositioning frequency [15] [16] [17] [18] [19], but it is interesting to note that the guideline cited earlier does not advocate this frequency and instead recommends determining a turning schedule based on the individual, making sure to take into account the patient’s comfort. As noted in Section II it is believed the two hour repositioning frequency comes from World War II clinics as that was the time it would take to turn every patient [20].

Several studies suggest additional nursing care to prevent pressure injuries, such as employing a full-time wound nurse [31] or using a reminder system [15]. Although these studies do present improvement in care the reliance on increasing the demands of the nursing staff may not be scalable in the U.S. as it is expected because of the aging baby boomer generation and the lack of nursing graduates in the U.S. there will be a nursing shortage [32]. In addition, two studies have found that repositioning does not always effectively redistribute load [33] [34], meaning even though healthcare staff may be following all guidelines to rotate patients on a schedule, because there is currently no standard way to objectively measure if a patient is correctly turned, pressure injuries will still form.

Several risk assessment scales have been developed over the years such as the Braden [35], Norton [36], Waterlow [37], and Cubbin and Jackson [38]. All scales are different, but they rely on a series of measurements recorded by a healthcare personnel, such as activity, age, nutrition, and incontinence. From these assessments a score is given and based on the score a patient is assigned a risk designation. Of these scales the Braden scale is the most studied [13], but none of the scales have been shown to be highly effective at predicting pressure injuries [13].

1) *Taxonomy Criteria:*

TABLE I: Taxonomy of pressure injury prevention strategies

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Active Prevention Strategies				
Nursing Guidelines	↑	↑	↓	. . .
Support Surfaces	↑	. . .	. . .	. . .
Nutrition	. . .	. . .	↓	. . .
Electrical Stimulation	↑	↑	↓	↓
Sensor-Based Risk-Factor Monitoring				
Pressure	↑	. . .	↑	↑
Temperature and Humidity	. . .	NA	↑	↑
Inertial Measurement Unit	↑	↑	↑	↑
Blood Flow	. . .	NA	↑	↑
Biomarker	↓	NA	↑	↑
Skin Integrity	. . .	NA	↑	↑
Electrocardiography	. . .	NA	↑	↑
Camera	. . .	NA	↑	↑
Ultrasound	. . .	NA	↑	↑
Impulse Radio Ultra Wide Band	. . .	NA	↑	↑
Leaking Coaxial	. . .	NA	↑	↑

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Active Prevention Strategies				
Nursing Guidelines	↑	↑	↓	. . .

Nursing guidelines are published by multiple organizations and therefore are **commercially available**. Evidence based guidelines are published by the NPUAP and recommendations such as repositioning the patient are based on **clinical trials** showing the effectiveness [30], so clinical trials support nursing guidelines. The downside of nursing guidelines is that they are **time** intensive for healthcare staff by necessity and therefore do not save time. Guidelines do request that appropriate changes are made by individual, this relies heavily on the staff expertise, but they can be **tuned to an individual**.

B. Support Surfaces

In order to stay consistent with the literature we will use the definitions by the NPUAP as part of their Support Surface Standards Initiative [39]. From these definitions a Support Surface is "a specialized device for pressure redistribution designed for management of tissue loads, micro-climate, and/or other therapeutic functions (i.e. any mattresses, integrated bed system, mattress replacement, overlay, or seat cushion, or seat cushion overlay)."

The categories of Support Surfaces are defined by the Support Surface Standards Initiative and are reproduced as follows:

- Air Fluidized — "A feature of a support surface that provides pressure redistribution via a fluid-like medium created by forcing air through beads as characterized by immersion and envelopment."
- Alternating Pressure — "A feature of a support surface that provides pressure redistribution via cyclic changes in loading and unloading as characterized by frequency, duration, amplitude, and rate of change parameters."
- Lateral Rotation — "A feature of a support surface that provides rotation about a longitudinal axis as characterized by degree of patient turn, duration, and frequency."
- Low Air Loss — "A feature of a support surface that provides a flow of air to assist in managing the heat and humidity (microclimate) of the skin."
- Reactive Support Surface — "A powered or non-powered support surface with the capability to change its load distribution properties only in response to applied load." This category would include Air Fluidized Mattresses/Overlays.
- Active Support Surface — "A powered support surface with the capability to change its load distribution properties, with or without applied load." This category would include Alternating Pressure and Lateral Rotation Mattresses/Overlays.

An extensive literature survey on Support Surfaces [40] that examines 59 Randomized Controlled Trials (RCTs) found that the effect of advanced Support Surfaces such as Air Fluidized, Alternating Pressure, Lateral Rotation, Low Air Loss, and Active Support Surfaces have on preventing pressure injuries is minimal. Several studies found these advanced types of mattresses to be better than "standard" mattresses, but "standard" is not well defined. In addition higher-specification foam as well as medical grade sheepskin were found to reduce pressure injuries better than standard mattresses at much lower cost than an advanced Support Surface. The authors conclude that more RCTs should be conducted on Alternating Pressure Mattresses in combination with other technologies such as Low Air Loss, the comfort of the patient should be considered in studies, and the cost effectiveness of the solution should also be considered.

Support Surface studies have been able to show that Active Support Surfaces can lower the peak pressure [41]. But the expert consensus with 100% agreement is that Support Surfaces cannot replace repositioning [42]. In addition evidence based guidelines set forth by the NPUAP also specify when using Support Surfaces patients should still be repositioned [30], although the frequency of repositioning can be adjusted.

The appeal of Support Surfaces is that a patient could be placed on such a surface and pressure injuries would not form, but there is no evidence that this is the case. Instead Support Surfaces are additional tools healthcare staff can use to help prevent pressure injuries, but still requiring active work from the staff.

1) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Active Prevention Strategies				
Support Surfaces	↑	. . .	. . .	. . .

Support Surfaces are **commercially available** from multiple companies, such as Hill-Rom, with various features. **Clinical trials** are somewhat mixed as they have shown that Support Surfaces are better than hospital mattresses, but repositioning is still required and in the case of Lateral Rotation or Alternating Pressure mattresses or overlays one can imagine they may not be the most comfortable mattress or cost effective. Support Surfaces may be able to save **time** for the clinician, by increasing the time between repositioning, but the amount of time is not known and therefore it is hard to say how much time is really saved. Some types of Support Surfaces are **tuned to the individual** such as Active and Reactive Support Surfaces as they adjust based on the patient, but other types are not.

C. Nutrition

Malnutrition is associated with the formation of pressure injuries [13] and it is also one of the factors on the Braden Scale [35]. The NPUAP Guide recommends screening patients at risk of pressure injuries to determine if they are malnourished and assessing weight loss, ability to eat independently, and whether the patient is getting appropriate nutrients [30].

Although nutrition is regarded as important to prevent pressure injuries a survey on nutrition in 2014 reviewed Randomized Controlled Trials that evaluate whether nutrition had any effect on pressure injury formation or healing and found no evidence to support nutrition as an effective way to reduce pressure injuries [43].

Another study aimed to address evidence-based nutritional needs of populations at risk for pressure injuries and concluded that nutrition and hydration are important, but future studies are needed to determine what specific supplements are needed [44]. In addition another study concludes that additional energy, protein, zinc, and Vitamins A, C, and E, amino acids arginine and glutamine have been documented to promote wound healing, although the ideal amount of each is not known [45].

There is one large RCT of 200 patients that showed that additional supplementation of arginine, zinc, and antioxidants to a diet that is already high in calories and protein provided improved pressure injury healing [46]. Although this work is significant researchers agree that an additional study is needed to confirm the results [47] [44].

1) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Active Prevention Strategies				
Nutrition	. . .	. . .	↓	. . .

Nutrition, i.e. food or supplements, are available **commercially**, but a protocol on the amount of nutrition needed is not known. **Clinical trials** are mostly favorable, but there is still some debate on what exact supplements are needed. To make sure that patients are eating as they should be and eating the required nutrients requires more work and **time** for healthcare staff. Nutrition can be **tuned to the individual**, but again this does take time for the staff to assess and administer and relies on the expertise of the healthcare staff.

D. Electrical Stimulation

Electrical Stimulation (ES) is a technique to contract the muscles, to simulate the natural movements that are made by a healthy individual when sitting or lying down. This method requires electrodes attached to the skin. A current is then passed through, which in turn contracts the muscles. The contraction of the gluteus muscles relieves pressure around the ischial turbosities and produces elevation in tissue oxygenation [48]. ES has also been tested and found to be a safe method of treatment [49].

The frequency of treatment to prevent pressure injuries is currently not known, but a RCT was conducted using two different types of Electrical Stimulation and found increased blood flow and wound area reduction when compared to the control group [50]. Other work has found that Electrical Stimulation has a positive effect on the healing of pressure injuries for patients with spinal-cord injuries [51]. In addition to the frequency of treatment the method of application is also not established, for instance the electrode configuration and waveforms applied differ in various studies, but ES has been shown with moderate evidence at its effectiveness at pressure injury prevention [52].

A wirelessly controlled ES device using a smartphone accompanied by a cloud based application to track history and provide analysis of the therapy was developed in [53] as a potential way to make ES easier to apply.

1) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Active Prevention Strategies				
Electrical Stimulation	↑	↑	↓	↓

Electrical stimulation devices are available **commercially**. **Clinical trials** have shown that Electrical Stimulation is an effective treatment of pressure injuries. Electrical Stimulation is somewhat **time** intensive to apply as the electrodes must be placed properly and healthcare staff must also verify that the therapy is functioning properly. ES is not **tuned to the individual** as it uses the same protocol for every patient, this may change in the future, but as of now current research therapies are not based on feedback of the individual besides verifying that the muscles are contracting.

VII. SENSOR-BASED RISK-FACTOR MONITORING

In the following sections we will discuss pressure injury prevention strategies that have the potential to monitor a patient without intervention of healthcare staff. These strategies comprise of a sensor component and a software component that monitors the sensor information and displays the data in a way that is beneficial to the healthcare provider. For example Pressure Monitoring, which will be discussed in Section VII-A is a popular Sensor-Based Risk-Factor Monitoring technique as commercial pressure overlays can be placed on top of a mattress and can automatically monitor and display the interface pressure of a patient against a surface without any active part of the healthcare staff. The displayed pressure map would otherwise be unknown and allows staff to make a more informed decision when repositioning a patient.

When considering devices that will be in contact with a patient's skin, which is common in this section, it is important to note that the device itself can cause a pressure injury. This phenomenon is highlighted at the end of Section VII.

In Section VII-B we will discuss Temperature and Humidity Monitoring, which we classify as a Sensor-Based Risk-Factor Monitoring technique as temperature and humidity can be sensed and monitored similarly to pressure by providing a map of the temperature and humidity of the body against a surface. In Section VII-C we will discuss approaches to prevent pressure injuries using Inertial Measurement Units (IMUs), which measure orientation and acceleration, to measure the amount of movement a patient makes in bed or when seated. We classify this as a Sensor-Based Risk-Factor Monitoring technique as IMU data can be sampled and the movements of the patient, including the time of last repositioning can be relayed without any active role of healthcare staff. In Section VII-D we will discuss methods to monitor blood flow. As of this writing Blood Flow Monitoring is limited to a certain area of the body and is still mostly a manual process, but we classify this technique as Sensor-Based Risk-Factor Monitoring as it has the potential to be an automatic process. In Section VII-E we will discuss biomarkers that can be tracked to predict pressure injuries. Biomarker tracking is currently a manual process, but it has the potential to be automated in the future, so we classify this technique as Sensor-Based Risk-Factor Monitoring. In Section VII-F we will discuss Skin Integrity Monitoring that can monitor the skin integrity at a certain location of a patient without any active role of healthcare staff, meaning the system itself will relay to the healthcare staff whether an area is at risk. In Section VII-G we will discuss techniques to monitor Electrocardiography (ECG) of a patient automatically and use this to detect the movements of a patient. In Section VII-H we will discuss using a camera to automatically assess the movements of a patient. In Section VII-I we will discuss using ultrasound as a way to assess an area for pressure injuries. Ultrasound as of this writing still relies on the healthcare staff, but with added software it could potentially automatically assess whether an area is at risk of a pressure injury. In Section VII-J we will discuss Impulse Radio Ultra Wide Band (IR-UWB) as a technique to automatically assess the movement of a patient. In Section VII-K we discuss Leaking Coaxial Cable, a technique that monitors the physical WiFi channel, to automatically detect the movement of a patient. In each subsection we will discuss the latest research as well as the taxonomy criteria as it applies to the respective technique: commercial availability, clinical trials, time savings, and whether the technique is tuned to the individual. In regards to the taxonomy each category of the taxonomy is evaluated on a complete system that both senses and presents information to healthcare staff, not just based on the senors themselves. For instance Electrocardiography machines are commercially available, but Electrocardiography Monitoring systems are not.

A common technique in this section is Posture Detection. In this work we use the term posture to describe the position of a patient on a mattress, e.g. left side, right side, or supine. The number of postures vary by paper, for instance some identify three postures [54] and others identify eight [55]. We display several of the more common postures in Figure 2.

Posture Detection is an important technique as it gives additional meaning to sensor data as the sensor data can be tracked per posture of the patient over time as well as tracking how often a patient is in each posture, which is also helpful to track turning schedules. In general these techniques either use machine learning techniques to predict a posture from past data or use geometric data to identify a posture.

Device-Acquired Pressure Injuries: It is important to note that patients with medical devices are at higher risk of developing pressure injuries [30]. If a patient has a medical device, as listed in Table II, they are 2.4 times more likely to develop a pressure injury [56]. Of all patients that form a pressure injury two reports publish 34.5% [56] and 32.8% [57] of the pressure injuries formed were from medical devices, verified visually, e.g. the redness of the pressure injury on the skin is in the shape of the medical device. We note these facts as it will be relevant to future applications to prevent pressure injuries. If a device is to sit on the skin of a patient the design of the device must take into consideration that the device itself could contribute to pressure injury formation.

TABLE II: Medical device listing from [56].

Anti-embolic stockings
Cervical collars
Endotracheal tubes/commercial endotracheal tube holders
Face masks for non-invasive positive pressure ventilation
Faecal containment devices
Nasal cannulas
Pulse oximetry probes
Radial artery catheters
Sequetial compression devices
Splints and braces
Urinary catheters

A. Pressure

Interface pressure sensing is the most extensively studied technique to monitor pressure injuries. In a literature survey of software solutions to prevent pressure injuries, including work up until 2013, out of 36 studies surveyed, 26 used pressure sensing [12]. Pressure based approaches break down into two main categories: Continuous Bedside Pressure Mapping (CBPM) and Posture Detection.

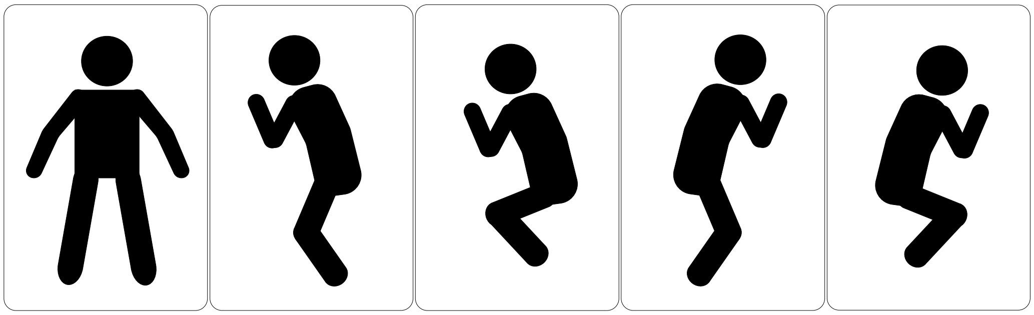
1) Continuous Bedside Pressure Mapping: Continuous Bedside Pressure Mapping (CBPM) uses a matrix of pressure sensors that is placed on top of a mattress. The pressure value at each location is displayed, usually on a tablet. The typical image that is displayed makes it very easy to see the outline of the patient's body as well as currently what areas of the body are experiencing the most pressure. CBPM systems are offered commercially from companies such as Wellsense, Tekscan, Vista-medical, Xsensor, Novel Electronics, and Sensor Products.

CBPM's biggest benefit is to help healthcare workers when positioning patients so that pressure is actually relieved as the CBPM system visually displays the current pressure distribution of the patient on the measured surface. As mentioned in Section VI-A, one study found that standard repositioning does not properly position patients to relieve pressure [33], but using CBPM it was found that healthcare staff were able to more effectively reposition patients [58] and reduce peak pressure [59]. Another study found that using CBPM the average time to turn a patient post alarm was reduced from 120 minutes to 44 minutes [60].

Two studies conducted controlled trials using CBPM and found that the CBPM group had a lower incidence of pressure injuries [61] [62], although in both studies the authors concede that more evidence is needed. A Randomized Controlled Trial was conducted using CBPM and found that there was no reduction in the CBPM group [63].

To address the concern that using CBPM a patient would not be able to be tracked when moved to a new hospital bed a study focused on a CBPM system that uses wireless pressure and temperature sensors attached to the patient's body by using Near Field Communication (NFC) [64]. The sensors were attached to high-risk areas of the body and powered through an antenna in the bed. A monitoring study was done on a sleeping patient and the sensors were verified to accurately collect data.

2) Pressure Posture Detection Algorithms: Pressure Posture Detection was recognized as an important area of research to monitor pressure injuries as detecting the current posture of the patient allows



(a) Supine (b) Right Yearner (c) Right Fetus (d) Left Yearner (e) Left Fetus

Fig. 2: Five common postures

for pressure tracking as the patient moves as opposed to an average or peak value.

Pressure Posture Detection algorithms work by reading a matrix of pressure sensors roughly the size of a mattress. The data read from a matrix of pressure sensors is generally referred to as a pressure map, as each pressure value is mapped to an x, y coordinate.

So far all work we are aware of in this area are conducted on small sample sizes of roughly 3-15 individuals and as far as we are aware have never been tested in a clinical setting. Recent work tends to focus on the accuracy of detecting the posture of a given algorithm.

Lower density custom pressure overlays were used in several works to classify postures, but with relatively low accuracy. In [54] the authors use a custom low density pressure sensor overlay, using rows of pressure sensors, and classify three postures with 78.7% accuracy by using the probability of a posture based on the distribution of pressures on the custom pressure sensor. An extension of this work using two new custom sensor layouts and using Principal Component Analysis (PCA) and Support Vector Machines (SVMs) to extract features of each posture in addition to using the probability of the pressure distributions were able to classify six postures with 83.5% accuracy [65]. To improve the accuracy of lower density pressure overlays several techniques were developed using an additional camera [66] [67]. With the addition of a camera one work was able to achieve 94% accuracy of 9 postures [66].

Higher density pressure-based Posture Detection techniques rely on a combination of image processing techniques, to pre-process the pressure map, and machine learning techniques to identify the posture. Several works use commercial pressure overlays that provide high density pressure maps. A somewhat earlier work using a commercial pressure overlay [68] was able to detect five postures with 98% accuracy. A subsequent work focused on higher speed classification and was able to classify 97% accuracy identifying eight postures [55].

A custom high density pressure overlay was used in two works [69] [70]. The algorithms in the work cited are designed for sleep monitoring, but these algorithms are also applicable for pressure injuries. The first work [69] was able to detect six postures with 83% accuracy. The second work [70] improved on this and were able to classify six postures with 91% accuracy.

Limb-identification is a subset of techniques in the category of Posture Detection that can track the individual limbs in addition to the posture allowing for pressure tracking of individual parts of the body as the patient turns. In addition to the benefits of Posture Detection, Limb-identification can warn if an individual part of the body is at risk, not just a certain posture. All Limb-identification algorithms found use high density pressure overlays.

An algorithm was developed to detect high pressure areas in [71] using a predefined skeleton template with 86% accuracy. Another algorithm was able to classify limbs with 92% accuracy in three different postures [72] by using clustering based on a predefined body map. Another work used pictorial structures of the body to detect limbs with 90% accuracy [73]. An algorithm that requires no predefined template was developed in [74] and was able to achieve 93% accuracy. Another technique developed to be fast and also does not require a predefined template was able to achieve 94% accuracy [75].

3) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Sensor-Based Risk-Factor Monitoring				
Pressure	↑	. . .	↑	↑

Pressure overlays that can continuously monitor pressure and display the pressure visually to healthcare staff are **commercially available**, such as Continuous Bedside Pressure Monitoring systems. **Clinical trials** are mixed with pressure based systems, some studies have shown a reduction in incidence while other studies did not. Pressure Monitoring does save **time** for staff, as an assessment of the pressure distribution is automatically displayed and with the addition of Posture Detection algorithms pressure-based systems have the potential to pinpoint which areas of the body are at high-risk, which otherwise would have to be done manually by healthcare staff. Pressure Monitoring is **tuned to the individual** as pressure is measured directly from the patient.

B. Temperature And Humidity

Temperature is often associated as a risk factor of pressure injuries, but as mentioned in Section IV it isn't clear how temperature relates to pressure injury formation. Humidity or moisture of the skin of the patient is also a risk factor, but the relation of humidity to pressure injury formation is not understood. In Section IV we mention that incontinent moisture can lead to Superficial Skin Injury, which are not related to Deep Tissue Injury and is therefore not by definition a pressure injury. Other factors such as an increase in moisture can lead to skin breakdown and a decrease in moisture can lead to cracking of the skin [76].

One study used a thermal camera to manually take pictures of the heels of patients, the idea being that the difference in temperature between the heels can be an indication of pressure injury formation [77]. Another study manually measured temperature, humidity (they call it moisture), and pressure and found that the difference in temperature between the affected area and the skin around the navel could indicate a pressure injury formation [76].

Most studies monitor temperature in addition to other factors, most notably pressure. One study used both a matrix of pressure sensors in addition to a matrix of temperature sensors to view both in real time [78]. In another study a wearable device was created that can measure pressure, temperature, and humidity [79]. A battery-free wireless sensor was developed in [64] that measures both pressure and temperature and can be placed on various parts of the body.

1) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Sensor-Based Risk-Factor Monitoring				
Temperature and Humidity	...	NA	↑	↑

Temperature and Humidity Monitoring systems have been developed in prototypes, but are not **commercially available**. No rigorous **clinical trials** have been tested with temperature and humidity systems. Prototype systems able to display real-time temperature and humidity information would be able to save **time** for healthcare staff as information would automatically be collected and displayed. Temperature and humidity would be measured directly from the patient and therefore would be **tuned to the individual**.

C. Inertial Measurement Unit

An Inertial Measurement Unit (IMU) is a device that reports movement. An IMU typically consists of accelerometers, that report acceleration, gyroscopes, that report angular velocity and orientation, and sometimes magnetometers, that report the magnetic field, which can be used to identify headings (e.g. North, South, East, West). IMU data is used to track steps in smart phones and also geographical location on airplanes.

There are several works that use IMU data to detect the posture of a patient in bed or just to monitor mobility as this can be an indicator of a patient at risk of pressure injuries. There are commercially available systems to monitor IMU data, one being Leaf Healthcare.

Posture detection using IMUs were used in a study using Wireless Identification and Sensing Platforms (WISPs) attached to a mattress to infer the posture of the patient [80]. Each WISP has an accelerometer that transmits data. Using this technique the authors were able to achieve 93% accuracy of classifying five postures. Another study used a single accelerometer to classify three postures with 99% accuracy [81]. Another study used three wearable [82] IMUs to detect four postures with 99.5% accuracy and eight postures with 93% accuracy.

Several works researched systems to monitor accelerometer data. One work investigated a system to monitor wearable accelerometer data and track it over time [83]. Another work investigated a system to monitor accelerometer and some pressure data in a mattress [84]. A real-time system that detects the posture of the patient using an accelerometer and takes a picture every time the posture changes was developed in [85].

A Randomized Controlled Trial was conducted using a wearable IMU and scheduled turning [16]. The trial found that there were significantly fewer pressure injuries in the intervention group and turning compliance was significantly higher in the intervention group. This study used a commercially available system by Leaf Healthcare. The authors note that a limitation of the system is that the device is placed on the trunk of the patient, meaning only trunk turning is detected, so extremities, such as the heels of the patient, are not monitored for compliance [16].

1) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Sensor-Based Risk-Factor Monitoring				
Inertial Measurement Unit	↑	↑	↑	↑

Inertial Measurement Unit (IMU) systems are **commercially available**. **Clinical trials** show that fewer pressure injuries occur when using an IMU system. IMU systems save healthcare staff **time** as they measure and report the activity of patients automatically. Activity is tracked based on the patient and is therefore **tuned to the individual**.

D. Blood Flow

As discussed previously, it is currently believed that ischemia, the lack of blood flow to the underlying tissue, and reperfusion, the reintroduction of blood to an ischemic region, are two causes of pressure injuries. One way to monitor ischemia and reperfusion can be by measuring blood flow to an area of the body. One such study monitored blood flow at the heel by using infrared sensors and were able to detect noticeable changes when the heel was under pressure [86].

Another study designed an optical probe that can be used to get continuous diffuse correlation spectroscopy and diffuse near-infrared spectroscopy to measure blood flow in a patient study [87]. They found that these may be useful methods in predicting pressure injuries.

1) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Sensor-Based Risk-Factor Monitoring				
Blood Flow	...	NA	↑	↑

Blood flow systems have only been developed in prototype and are not **commercially available**. No **clinical trials** have been conducted using Blood Flow Monitoring. A potential blood flow system that can monitor blood flow and present this data to healthcare staff is not currently developed, but potentially would save healthcare staff **time**. Blood flow is monitored based on the patient and is therefore **tuned to the individual**.

E. Biomarker

Biomarkers are measurable biochemical substances that can be used to predict an event, in this case a pressure injury. Some studies show that sweat lactate and Cytokines can be tracked to detect skin breakdown, which would be indicative of a Stage 1 pressure injury [6]. To detect deeper level pressure injuries C-reactive protein (CRP) can be monitored in blood [6]. Currently these monitoring strategies are not developed as a system, but instead can be tested from blood or sweat. Another study found that serum albumin had an inverse relationship to pressure injury formation, so the lower the serum albumin the higher likelihood of pressure injury formation [88]. This finding is in agreement with previous studies as low serum albumin is an indicator of malnutrition and as discussed in Section VI-C it is accepted that malnutrition is associated with pressure injury formation.

A flexible wearable biochemical sensing device that analyzes sweat was developed and tested in a healthy patient population [89]. The device can communicate analysis over Bluetooth. The applications mentioned in the paper are not specifically for pressure injuries, but as sweat lactate is a biomarker for pressure injuries this is a promising biochemical sensor that could be used for pressure injury prevention.

1) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Sensor-Based Risk-Factor Monitoring				
Biomarker	↓	NA	↑	↑

Biomarker work is purely based on testing blood or sweat from the body and does not currently use a biochemical sensor. In the future a system that could automatically monitor biomarkers may be possible, but as of now these systems are not **commercially available**. Currently an automatic biomarker system is not developed so no **clinical trials** have been run. A biomarker system would potentially save healthcare staff **time**. Biomarkers would be measured directly from the patient and would therefore be **tuned to the individual**.

F. Skin Integrity

Skin Integrity Monitoring is a technique to monitor the skin for water loss, pH, moisture, elasticity, and color. Although these techniques offer promise the variation between patients and ambient conditions are currently not studied in depth enough at this point in time to be a consistent way to monitor or identify pressure injuries [6]. In addition these types of sensors are ideal for measuring a specific site to test for pressure injury formation as opposed to predicting a pressure injury.

A new bandage-based sensor used to measure the skin integrity via skin impedance spectroscopy was developed and was able to test in rat models that the integrity of the skin had a direct correlation with impedance [90] and may be a possible way to detect pressure injuries. The idea behind this technology is that the skin acts as a capacitor, with the skin layer acting as the dielectric. As the skin breaks down the dielectric layer's permittivity changes thereby giving a change in measurement.

Additionally a commercial company Bruin Electronics makes a hand held device called the SEM Scanner that can run impedance spectroscopy on the skin that can also detect skin damage [91], which can be used to detect pressure injuries.

1) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Sensor-Based Risk-Factor Monitoring				
Skin Integrity	. . .	NA	↑	↑

Skin Integrity Monitoring sensors and devices are commercially available, but a system to monitor the sensor is not **commercially available**. It is important to note that our criteria for commercial availability implies the ability to operate without healthcare staff intervention. As such we classify handheld devices, whose operation requires healthcare staff, as ”neutral” regarding their commercial availability. No **clinical trials** were run using Skin Integrity Monitoring. Such a system to monitor the skin would save **time** for healthcare staff as the system could automatically measure the skin integrity and present the data to the healthcare staff. The measurements would come directly from the patient and therefore would be **tuned to the individual**.

G. Electrocardiography

There are a few works that monitor Electrocardiography (ECG) to detect the posture of a patient. An Electrocardiogram uses electrodes to monitor the electrical activity of the heart. ECG Monitoring is more applicable to sleep monitoring as it has been found to detect sleep apnea [92], but the posture classification aspect of the technique could be applied to pressure injuries.

One study used a custom ECG monitor overlay and applied a machine learning technique to classify the posture of a patient. The study found they were able to achieve very high accuracy at 98.4% of four postures [93].

1) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Sensor-Based Risk-Factor Monitoring				
Electrocardio -graphy	. . .	NA	↑	↑

An Electrocardiography (ECG) Monitoring system was developed in prototype, but is not **commercially available**. No **clinical trials** using ECG Monitoring have been run. Such a system would save healthcare staff **time** as ECG data would be monitored and presented automatically to healthcare staff. The data would be measured directly from the patient and is therefore **tuned to the individual**.

H. Camera

Image processing techniques are very common, such as facial recognition built into many smartphones. A camera is a non-invasive way to monitor a patient using image processing techniques to monitor the posture and mobility of the patient. The issue of privacy is often brought up when using a camera and the most frequent approach to avoid privacy issues is by using techniques to remove the details of the image, so that the outline of the body can be determined, but not the face or any other recognizable features.

In [94] the authors develop a system to monitor patients using a depth camera, to block out features, with the goal of classifying postures and monitoring activity. The system can also notify healthcare staff if repositioning is required. In [95] the authors classify three postures based on a depth camera with an accuracy of 94%. Another work also used a depth camera and was able to classify 10 postures with 93% accuracy, but when a quilt was laid on top of the subject, the accuracy was reduced to 89% [96].

Several works use a camera in addition to other sensors. In one work a camera with a polarizer is used in addition to two types of infrared cameras to monitor the size of a pressure ulcer [97]. The following works were mentioned in Section VII-A, but in addition to pressure they also use a camera to improve their posture classification [67] [66].

1) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Sensor-Based Risk-Factor Monitoring				
Camera	. . .	NA	↑	↑

Camera Monitoring systems to measure the activity of a patient are in prototype, but are not **commercially available**. **Clinical trials** have not been conducted on Camera Monitoring systems. A system would be able to automatically measure the movements of a patient and present the information to the healthcare staff, thereby saving **time**. The movements of a patient would be based on the individual, so that activity is **tuned to the individual**.

I. Ultrasound

Ultrasound waves are sound waves above the range of human hearing. Several studies have found high frequency ultrasound imaging, using the reflected ultrasound waves to construct an image of the underlying tissue and muscle, a possible way to monitor pressure injuries. A study confirmed that when examining pressure injuries ultrasound imaging was able to visualize the damage beneath the skin [98], but the authors admit that ultrasound imaging needs a certain level of skill to assess the images. Another study concluded similarly that ultrasound is a promising technology, but more work needs to be done on interpreting scans [99].

1) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Sensor-Based Risk-Factor Monitoring				
Ultrasound	...	NA	↑	↑

Ultrasound devices exist commercially, but a system to automatically use ultrasound to monitor for pressure injuries does not exist **commercially**. **Clinical trials** have not been run on an Ultrasound Monitoring system. Such as system would save healthcare staff **time** as it would automatically assess whether a patient has a pressure injury. Ultrasound measurements would be directly from the patient and could assess the **individual**.

J. Impulse Radio Ultra Wide Band

Impulse Radio Ultra Wide Band (IR-UWB) radar is a technique that uses the time of reflection of an electromagnetic pulse to extract information about the reflected surface, which has been used to detect heart rate and respiration rate [100]. A study found that in addition they were able to use IR-UWB to detect four postures with 89% accuracy [100].

1) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Sensor-Based Risk-Factor Monitoring				
Impulse Radio Ultra Wide Band	...	NA	↑	↑

An Impulse Radio Ultra Wide Band (IR-UWB) system to measure the activity of a patient exists in prototype, but is not **commercially available**. **Clinical trials** have not been run for such a system. An IR-UWB Monitoring system would save healthcare staff **time** as it would automatically measure and assess the activity of a patient. The system would also be **tuned to the individual** as activity would be based directly on measurements from the patient.

K. Leaking Coaxial

There is one approach at the time of writing that uses a "Leaking Coaxial Cable", i.e. reading the physical characteristics of a coaxial cable, a type of transmission cable, through a WiFi router. The subtle movements of a patient cause enough of a change when reading from the coaxial cable that a study was conducted to explore the ability to predict the posture of the patient, although the accuracy is not reported [101].

1) Taxonomy Criteria:

Application	Commercial Availability	Clinical Trials	Time Savings	Tuned To Individual
Sensor-Based Risk-Factor Monitoring				
Leaking Coaxial	...	NA	↑	↑

A Leaking Coaxial system was developed in prototype, but is not **commercially available**. **Clinical trials** have not been run on such a system. A Leaking Coaxial system would save healthcare staff **time** as it would be able to automatically assess the activity of a patient. The system would also be **tuned to the individual** as measurements would be directly from the patient.

VIII. Discussion

Based on our taxonomy, as seen in Table I, we find the most promising currently researched techniques to prevent pressure injuries are Electrical Stimulation, Pressure Monitoring, and Inertial Measurement Unit Monitoring. We find the most promising strategy for the future to be Biomarker Monitoring. Each technique in isolation has its own advantages which we will discuss, but a system that implements all techniques may be the most effective at reducing pressure injuries. It is also important to note that these techniques are supplementary to nursing guidelines, a mainstay of pressure injury prevention.

We find many Sensor-Based Risk-Factor Monitoring techniques promising, but they are not implemented as a viable system in a clinical setting, e.g. the algorithm is tested on pre-collected data and does not discuss ways to present this data back to the healthcare staff. Some examples of such techniques are Blood Flow Monitoring (Section VII-D), as blood flow is a key component of pressure injury formation, Skin Integrity Monitoring (Section VII-F), as the integrity of the skin can be an indicator of a pressure injury formation, and Camera Monitoring (Section VII-H), as cameras are easy and cheap to deploy. But, all of the mentioned techniques do not have a clinical system to gather the data, analyze the data, and present it back to healthcare staff. We think this shows the need for a clinical software system that can use custom sensors, custom analysis algorithms while keeping data secure, and present data back to the healthcare staff in a customizable way. Such software would lower the barrier of entry of implementing a sensor-based technique designed for a clinical setting.

Electrical Stimulation uses electric current to stimulate muscles, which requires placing electrodes around a high-risk pressure injury area with healthcare staff supervision. From our taxonomy Electrical Stimulation is commercially available and backed by clinical trials, but it is a time-intensive strategy as it requires the nursing staff to put on the device and verify it is working properly as well as continually monitor the device throughout a session. In order for Electrical Stimulation to be applied preventively it would have to be applied at every high-risk area of the body, which would increase the time intensive nature of this technique. Electrical Stimulation offers the best fully autonomous solution, as potentially a system could be developed that could continuously stimulate the muscles of a patient, which could potentially eliminate a pressure injury from forming. But, such a system would have to be rigorously safety tested and also developed in such a way that it does not interfere with the patient's quality of life.

Pressure Monitoring uses a matrix of pressure sensors to continuously monitor the interface pressure between a patient and a surface, typically a mattress or a chair. From our taxonomy Pressure Monitoring is commercially available, saves healthcare staff time, and can be tuned to the individual, but more clinical trials are needed to validate the technique as one trial showed a reduction in pressure injuries, while another trial showed no reduction. Pressure Monitoring is the most intuitive technique to prevent pressure injuries because it is well established, as discussed in Section IV, that pressure is the primary cause of pressure injuries. The current Pressure Monitoring systems available are limited to displaying the real-time pressure (Continuous Bedside Pressure Monitoring, CBPM) and cannot track the pressure as the patient changes posture or orientation. In addition to detecting buildups in pressure this technique also offers the advantage of studying pressure distributions over time.

One limitation to a CBPM system is that it cannot track the amount of pressure as the patient rotates, but there are several algorithms that can be used to avoid this limitation. A class of algorithms to process pressure map data are Limb-identification algorithms that can identify the individual parts of the body in various positions. This allows for the tracking of pressure per body part as the patient moves. Limb-identification algorithms are not currently tested in a clinical setting, but offer a promising way of detecting at-risk areas automatically, potentially saving healthcare staff having to periodically manually check the patient. A potential Pressure Monitoring system with Limb-identification offers the best non-invasive way to pinpoint areas of the body that are at risk of developing a pressure injury. The sensors used to monitor pressure are commercially available, it is only the software that needs to be developed in a commercial system.

Inertial Measurement Unit (IMU) Monitoring monitors the movements of a patient. From our taxonomy IMU Monitoring is commercially available, backed by clinical trials, saves time for healthcare staff, and can be tuned to the individual. IMU Monitoring is also inexpensive and can be built very small, the entire device including the ability to communicate over a network can be the size of a square inch button. When fixed to a patient an IMU Monitoring system can track how long a patient was in a fixed position. As the patient moves the IMU device tracks the movement and can display to healthcare staff how long a patient was in a certain posture and what the recommended next posture should be to allow reperfusion. If you had to choose a pressure injury prevention system today IMU Monitoring is the best option as it is commercially available and clinically verified.

Biomarker Monitoring tracks specific biochemicals in the blood and sweat to determine skin breakdown. From our taxonomy Biomarker Monitoring can save healthcare staff time and can be tuned to the individual, but is not commercially available and no prototype Biomarker Monitoring system exists and therefore has not been clinically verified, but the biochemicals to track are researched, but currently such a system would have to rely on manually testing the blood and sweat of a patient. If a specialized biochemical sensor is developed to test skin breakdown automatically, this may also be a promising solution. Biomarker Monitoring offers the most promise as it would directly detect pressure injury formation from the patient's biochemistry, but an established biochemical sensor for this application still needs to be researched and developed.

We see one of the biggest barriers for promising Sensor-Based Risk-Factor Monitoring techniques is the lack of a monitoring system that can collect sensor data, store and analyze the data securely, and present the data back to healthcare staff in a customizable way. Currently the only Sensor-Based Risk-Factor Monitoring clinical trials reviewed in this work, CBPM and IMU Monitoring, are commercial systems that are made exclusively for the respective technique. We see the need for a software system that can be modified easily to use different types of sensors, as well as different types of analysis, in a secure manner. This would allow for more clinical trials and more sensors to be used to reduce pressure injuries at a lower barrier of entry.

IX. Conclusion

Pressure injuries are currently an ongoing obstacle in healthcare. Pressure injuries are classified as "never events" as they should never occur and yet they are still present. In addition they are costly to treat, but more importantly they impact the quality of life of the patient as they are painful and impact the social life of the patient. Additionally current accepted nursing guidelines and interventions may not be enough to eliminate pressure injuries from occurring as they are time intensive and in the U.S. it is predicted there will be a nursing shortage in the future.

Modern pressure injury research primarily started after World War II and began with studies focusing on a pressure-time threshold that would be able to predict the formation of a pressure injury. Today it is accepted that no such singular threshold exists as it is highly dependent on the individual patient. In addition it is believed that some pressure injuries may be unavoidable even when using all of the accepted practices of prevention, but the percentage of unavoidable pressure injuries is not established.

It is currently understood that the biomechanics that cause pressure injuries are from pressure closing capillaries causing tissue to become ischemic, when under high pressure the closure of larger vessels causing thrombosis, the inflammation caused by the introduction of blood into an ischemic region, the closure of lymphatic vessels causing a buildup of metabolic waste products, and the deformation of tissue cells.

We surveyed the literature to find the latest research on preventing pressure injuries. Based on our findings the current research on prevention of pressure injuries can be broken down into Active Prevention Strategies and Sensor-Based Risk-Factor Monitoring. Active Prevention Strategies require an active role from healthcare staff and will most likely be a mainstay of current practice. Sensor-Based Risk-Factor Monitoring uses a variety of different types of sensors and a software platform that monitors the current condition of a patient and presents this data in an intelligible way to the healthcare staff, saving healthcare staff time as they do not need to manually go through this process.

To evaluate the current techniques we created a taxonomy that evaluates every category of technique based on its commercial availability, support of clinical trials, healthcare staff time savings, and whether the technique can be tuned to an individual. We note that not all techniques are mutually exclusive, for instance nursing guidelines are a mainstay of pressure injury prevention regardless of technique, but additional techniques, such as Pressure Monitoring may be able to reduce the time it takes for healthcare staff to follow nursing guidelines as part of the process is handled automatically.

Based on our findings the most promising techniques currently researched that have the most benefit in addition to nursing guidelines are Electrical Stimulation, Pressure Monitoring, and IMU Monitoring. The most promising future strategy is Biomarker Monitoring.

In addition many of the Sensor-Based Risk-Factor Monitoring techniques are promising, but they are not tested in a clinical setting making them hard to determine whether they will actually work. We believe there is an opportunity for a software system that can easily monitor sensor data, store the sensor data in a secure server, and present it back to healthcare providers. Such a system will lower the barrier of entry to test new Sensor-Based Risk-Factor Monitoring techniques that can monitor data that would otherwise have to be collected manually by healthcare staff thereby saving staff time.

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