How Can Sensor Systems Play a Role in the Monitoring and Prevention of Pressure Injuries in ICU Patients?

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Abstract

Objective To examine the monitoring and prevention of hospital-acquired pressure injuries in intensive care units.

Design Qualitative study of ICU nurses with pressure injury experience based on Evette's biological, psychological, and interpersonal dynamics theory.

Setting Semi-structured interview with experienced ICU nurses and passive observation of ICU staff performing a prone patient manual repositioning.

Participants Highly experienced Australian ICU nurses holding academic positions at QUT and Herston Biofabrication Institute research fellows.

Results Prolonged and persistent pressure on the skin can result in pressure injury, a common problem in patients with limited or no mobility due to health issues. Critically ill patients in hospitals, especially in intensive care units, are more prone to develop pressure injuries. Pressure injuries result in more extended hospital stays and costly treatments and significantly impact patients' quality of life. Even though the prediction and monitoring of pressure injuries are highly feasible by relying on assessment tools, staff expertise, and various digital devices, the prevention is still a challenge because of the task's labour-intensive nature. Depend on the lying orientation of the patient, skin integrity and some other factors, pressure injuries occur in different parts of the body: Occipital areas, shoulders, sacrum, and heels when the patient is in supine mode; and forehead, eyebrows, ears, chin, shoulders, knees, female breasts and male genitalia in prone mode. Alleviating pressure injuries in mechanically ventilated patients are more complex: Endotracheal and nasal gastric tubes can harm the corner of the mouth and nostrils since access to those areas are limited with the patient facing down and held in place by supporting surfaces. An experienced ICU staff should guide the team and keep the tubes in place while rotating the patient.

Conclusion Research highlighted that preventing the development of pressure injuries in an ICU setting does not have a high priority, and there are not enough adequate preventative support surfaces and equipoment. Therefore the lack of customised or individualised support surfaces can be an opportunity for using sensors in combination with emerging technologies such as additive manufacturing to provide more effective preventative measures.

Final Design The design-led research resulted in designing and prototyping an open source design-aid product to help designers and engineers who want to create proning pillows and face supports; monitor and record the pressure [from the pillow or cushion] on the face in specific areas that are more susceptible to developing pressure injuries.

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CHAPTER I
INTRODUCTION

Introduction

Pressure injuries (PIs), also known as pressure ulcers (PUs) or bedsores, are centralised damage to the skin and underlying soft tissue resulting from persistent pressure on the skin. Critically ill patients in intensive care units (ICUs) at hospitals, who have very limited or no mobility due to sedation or ventilation (sometimes with catheters and tubes attached to their bodies), are particularly at higher risk of developing skin breakdown.

The development of PIs among inpatients has a significant impact on their quality of life and causes prolonged hospital stays, forces high costs of treatment and requires intensive nursing care. In that regard, multiple assessment tools have been developed and readjusted over the years to prevent the development of PIs in the clinical setting. Studies show that PIs are mainly preventable by well-applied preventative measures. However, with an increasing number of hospital-acquired pressure injuries (HAPIs), PIs remain a significant clinical problem.

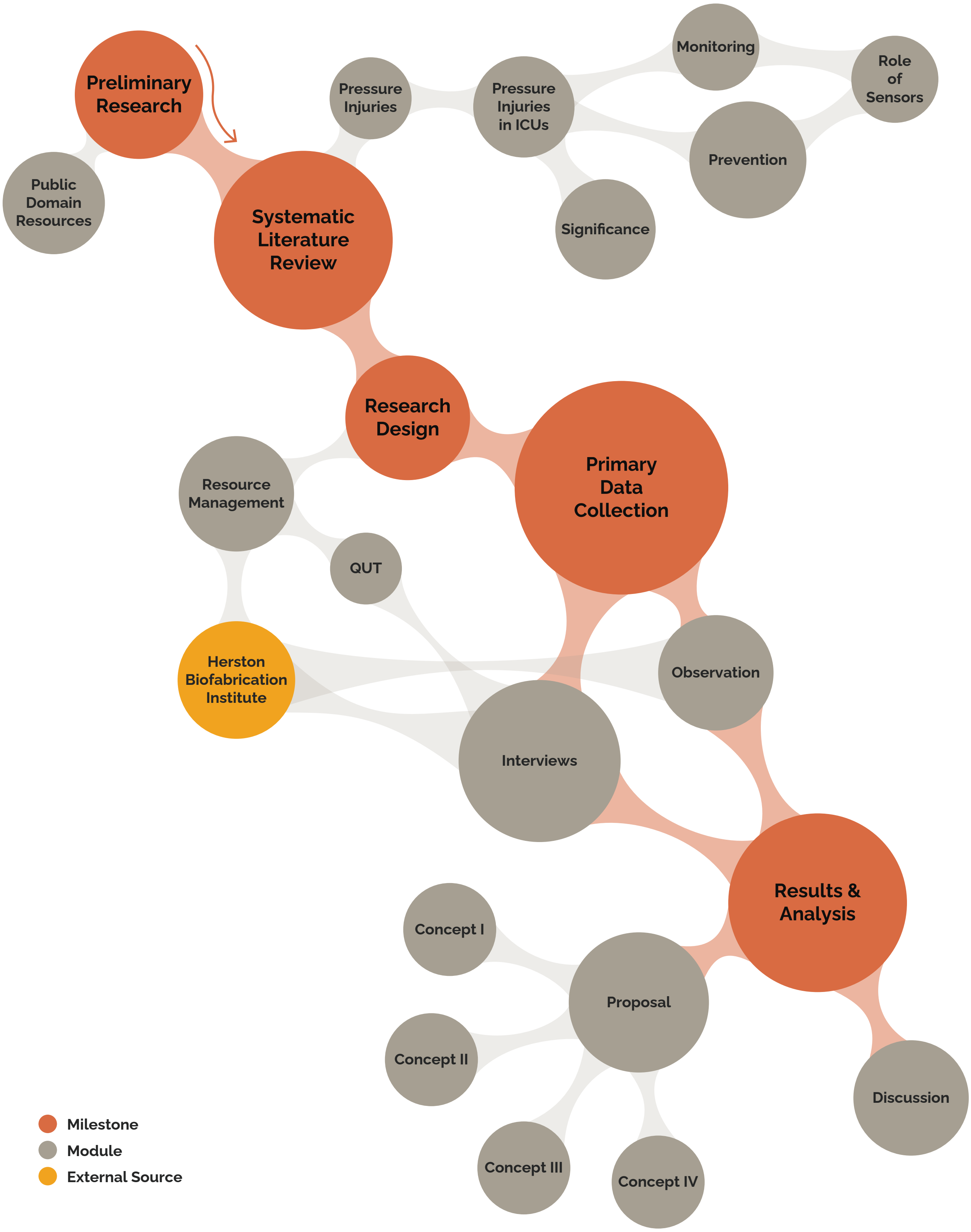
Development of PI needs time; therefore, constant monitoring of the patient in ICU is essential to conduct a thorough preventive measure. Multiple companies have developed various wearables/devices to monitor body parts under pressure. Wearable devices use sensors such as accelerometers and magnetometers to record body movements. In contrast, fixed devices mostly use different pressure sensors embedded in or under the mattress or the hospital bed to calculate the weight distribution throughout the time. Conventionally, these devices' data is used to alert nurses to go and manually reposition the patient or support surfaces such as cushions. Repositioning the patients is a labour-intensive task and gets more complex when the patient is placed prone. Some products, such as active air mattresses, reduce the risk of PI development by constantly inflating and deflating the internal air cells. Apart from the high costs of such products, some disadvantages make them less effective for medium-risk patients.

A review of the literature found that despite a large number of attempts to map, monitor, and record the pressure zones on the skin, there are only a few products that are designed to essentially prevent the development of PIs with no or very little human intervention. Sensors' data has been used to produce individualised pressure maps; however, no evidence of customised/individualised PI preventive products has been found.

This review of the literature which is part of phase 1 of the "Role of sensor systems in monitoring and prevention of facial PIs in ICU patients" project (Figure 1), is directed at PI in ICU patients, with an emphasis on the monitoring and prevention of pressure ulcer development using sensor-based systems and products. Phase 2 will answer the research questions and provide an appropriate design proposal.

Figure 1

Overall research dissertation structure in five phases.



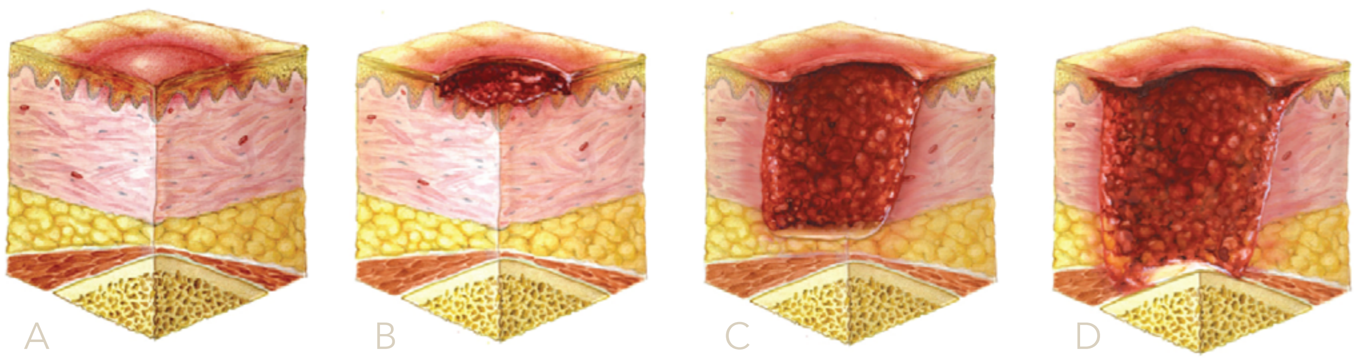
CHAPTER II
LITERATURE REVIEW

Pressure Injury

Pressure injury (PI) also known as pressure ulcer (PU) is a localised area of skin damage (Figure 2), caused by pressure, friction, or malnutrition in people with limited or no mobility due to health or impaired nutrition issues (Peko, Barakat-Johnson, & Gefen, 2020; Santy-Tomlinson & Limbert, 2020). In other words, if the capillary pressures in soft tissue and underlying layers exceed the normal range (16 - 33mmHg) due to external pressure, microcirculation gets disrupted and leads to a deleterious effect on tissue. High or low body mass index (BMI), decreased nutritional intake, and oedema are general risk factors of PIs (Werthman, Lynch, Ware, & Caffrey, 2019).

Figure 2

3D illustration of tissue sections of PI development stages. A) Stage 1 with red and hardened skin surface. B) Stage 2 with broken epidermis (topmost layer of the skin). C) Stage 3 with the wound extended to dermis (2nd layer of the skin). D) Stage 4 with the wound extended to the bone through the muscle.



Note. From *Recognizing and Treating Pressure Sores* by MSKTC, 2021 (https://msktc.org/sci/factsheets/skincare/Recognizing-and-Treating-Pressure-Sores)

Pressure Injury in ICU Patients

Due to the lack of mobility and impaired consciousness caused by sedation and anaesthesia, patients in the intensive care unit (ICU) are particularly at risk of PIs. Also, concentrating the ICU staff on critical care for life-threatening situations reduces the focus on lower priority care such as PI prevention (Minton, Batten, & Huntington, 2018; Santy-Tomlinson & Limbert, 2020).

Based on a study by Peko et al. (2020), the risk of PIs increases by 3.3 times when patients are placed prone as oppose to supine for spinal surgeries or where access to the back of the head or neck is required. The prone position is also critical for mechanically ventilated patients rising drastically in ICUs worldwide because of the coronavirus 2019 disease (COVID-19), where patients are susceptible to facial PIs during the 9 to 24 hours prone ventilation sessions.

Predicting the development of PIs is feasible; however, since it is highly dependent on ICU staff expertise, preventing them has been a challenge. Offloading the head is the most difficult compared to offloading other parts of the body, especially in ICU patients at an increased risk of PIs (Werthman et al., 2019).

Significance

Despite the significant amount of available guidance to manage PIs, they still represent a serious threat to patient's safety and can result in a more extended hospital stay and morbidity (Santy-Tomlinson & Limbert, 2020; Werthman et al., 2019). Every one in five hospitalised patient develops pressures injuries (Wåhlin, Ek, Lindgren, Geijer, & Årestedt, 2020).

The treatment cost of hospital-acquired pressure injuries (HAPI) in the US. is between US$9.1 to 11 billion, and PI related events are the cause of death for over 60,000 patients each year (Peko et al., 2020; Werthman et al., 2019). In addition to longer hospital stays and extra medical costs, PIs profoundly impact patients' quality of life (QOL) (Larcher Caliri, 2005), so the need for monitoring and prevention is clear.

Risk Assessment

According to Kottner and Dassen (2010), validated tools to stage and predict PIs included but not limited to Braden Scale (Appendix A-1), Waterlow Score (Appendix A-2) and Norton Scale (Appendix A-3). The authors do not recommend the Braden and Waterflow Scales for use in ICUs. Wåhlin et al. (2020) agree on the latter but argue that Norton is also more general and not reliable in an ICU context. They suggest that the Risk Assessment Pressure Ulcer Scale (RAPS), commonly used in Sweden, is a more valid and clinically useful tool. RAPS (Appendix A-4) is an enhanced version of Braden and Norton scales combined.

Based on another evaluative study by Efteli and Güneş (2020), the highest sensitivity, the highest specificity, and the highest positive predictive value determine by Waterlow Scale, Douglas Scale, and Fragment Scale, respectively. The authors also propose another tool called EFGU Pressure Ulcer Risk Assessment Scale (Figure 3), which shows a better and more reliable result than existing assessment tools. Jackson/Cubbin pressure ulcer scale is another tool developed explicitly for ICU; however, it has several items that do not contribute to the total risk score in developing PIs.

The most significant risk assessment result is that interventions are applied to manage all the risk factors; however, many tools do not consider frequently used medical devices in ICUs, forcing pressure on the skin and resulting in skin breakdown. Such devices are included but not limited to percutaneous and central cannulas and lines, anti-embolic stockings, mechanical ventilator tubing, oxygen tubing and face masks, endotracheal tubes, tracheostomies and the associated tubes and ties, nasogastric tubing, and chest or surgical drains (Santy-Tomlinson & Limbert, 2020).

Figure 3

EFGU Pressure Ulcer Risk Assessment Scale

Skin status in areas exposed to pressure		Incontinence (urine/feces)		Age (years)		Ability to make small movement/position shift in areas exposed to pressure*	
Healthy tissue	0	No	0	65 and under	0	1 shift per hour	0
Think/sensetive	1	Catheter inserted	0	>65	1	1 short every 2 hours	1
Edematous	1	Urinary incontinence	1			1 shift every 4 hours	2
Moist/cold	1	Fecal incontinece	2			Cannot make shift	3
Hypermia	2						
Discomfort and pain sensation in areas exposed to pressure		**Diastolic blood pressure (average per day)**		**Diabetes**		**Skin tolerance test (10 second assessment of blanching)**	
No discomfort or pain	0	60mm Hg or higher	0	No	0	Blanches/returns to normal	0
Discomfort and pain	1	<60 mm Hg	1	Yes	1	Blanches/returns to normal later	1
No sensory perception	2					No blanching	2

* small repositioning shifts at least 15° to 20 ° that take 60 seconds

Note. From *The Efteli and Güneş (EFGU) Pressure Ulcer Risk Assessment Scale Scoring* by Empirical Research, 2020 (https://qut.primo.exlibrisgroup.com/discovery/fulldisplay?docid=cdi_proquest_miscellaneous_2390652570&context=PC&vid=61QUT_INST:61QUT&lang=en&search_scope=MyInst_and_CI&adaptor=Primo

Sensor-based Monitoring

Frequently offloading the body part under pressure (either by repositioning the patient or relocating the support surface) is the main factor of preventing the development of PIs. Since the nursing interventions are proved to be insufficient (especially at night shifts), an accurate monitoring platform/device could play a significant role in preventing PIs (Hayn et al., 2015; Minteer et al., 2020). There are various sensing principles to help monitor interface pressures, including pressure-sensitive sensors, piezoresistive sensors, air-pressure appreciation sensors, and conductive-ink film sensors (Sakai et al., 2009). Some of the recent approaches toward monitoring the development of PIs are listed below:

- Minteer et al. (2020) recommend "PUMP1" and "PUMP2", which are reusable and low-cost repositioning monitoring devices. "PUMP1" is a wearable device equipped with sensors (an accelerometer, a gyroscope, and a magnetometer) that fits on clothing near the chest and stores the data from monitoring patient's rotation in a secure digital card (SD card).

- "PUMP2" is a multipart device that sits under each wheel of a hospital bed and measures the oscillations in weight distribution by constantly comparing the data retrieved from 4 load-cells under each wheel pad.

- "EarlySense" is a low-acuity continuous monitoring device (Figure 4) that records bed motions with the help of a piezoelectric sensor (Figure 5) in addition to heart and respiration rates. The results can be viewed on a computer in real-time. In addition to real-time visual representations of data, alerts can be sent to a nurse's cell phone or pager (Helfand, Christensen, & Anderson, 2011).

- "Measure X" by "SensorEdge" is a shape conforming pressure mapping device that provides a real-time graphical pressure map (Werthman et al., 2019).

- "KINOTEX" by "NITTA Corp." is a soft and robust fibre optic tactile sensor that monitors interface pressures of the whole body (Sakai et al., 2009).

- The "Leaf Patient Monitoring System" wearable by "Leaf Healthcare Inc." records the degree and duration of changes in body position and calculates optimal turning practice feedbacks (Pickham, Berte, et al., 2018).

- "Elextext", a smart textile woven in three layers, senses, monitors, and reports the location and intensity of pressure while placed between the body part and bed surface.

- Similar to the previous approach, "Wellness USA" introduced "The MAP". A smart coverlet with built-in pressure sensors for complete monitoring, alerting and protecting solution. "The MAP" identifies the build-up of pressure over time and displays a live and colour-coded pressure distribution map on a side monitor. The system sends alerts to nurses when a patient's periodic body repositioning is due ("New technology prevents pressure ulcers," 2011).

The drawback of a pressure sensor in monitoring devices is that the sensor output will not be accurate if bent, wrinkled, or hammocked. Given most of the pressure sensors are not durable and pliable, they are not suitable for repetitive use in the clinical setting (Sakai et al., 2009).

Figure 4

Wall mount EarlySense display helps clinicians continuously monitor their patients.

Note. From *Contact-Free Continuous Monitoring Solutions* by EarlySense Proactive Patient Care, 2021 (https://www.earlysense.com/)

Figure 5

A nurse is placing the piezoelectric pressure sensor pad under the mattress.

Note. From *Contact-Free Continuous Monitoring Solutions* by EarlySense Proactive Patient Care, 2021 (https://www.earlysense.com/)

PI Prevention Methods/Products

Current prevention guidelines set by American and European institutes for preventing pressure injuries suggest frequent repositioning of the patient (turning the body) and use of appropriate support surfaces to reduce interface pressure in a clinical setting. It is crucial to note that support surfaces are not fully effective in isolation and several preventative actions have to be applied in parallel (Haesler & Carville, 2015).

The standard repositioning interval for ICU patients is every two hours if in bed and every hour if in a chair (Pickham, Berte, et al., 2018; Sakai et al., 2009). However, Peko et al. (2020) argue that repositioning a prone patient is not an option in operation rooms and is very limited and labour-intensive in mechanically ventilated COVID-19 patients due to various types of attachment of monitors tubes and probes. Low compliance of turning protocols in ICU patients primarily relate to males with high BMI and low Braden score (Pickham, Pihulic, et al., 2018).

- The innovative active or passive support products such as "Specialty Pressure Redistributing Mattress" by "Hill Rom, Total Care bed" and "Fluidised Positioner Pillows" by "Monlycke ZFlow" mainly focus on evenly distributing pressure on the body surface to prevent the development of PIs.

- Alternating pressure air mattresses (APAMs) (Figure 6) reduce the pressure by consecutive inflation and deflation of air cells (Santy-Tomlinson & Limbert, 2020) or by using smart fluids. Smart fluids are gelatinous material that harden and soften in response to electrical stimuli (Ajami & Khaleghi, 2015).

- Passive mattresses, which generally made out of materials (foam, gel, air-filled, etc.), conform to the patient's body shape and distribute the pressure to a larger area. Active mattresses (e.g. pneumatic), on the other hand, contain several air chambers that automatically inflate and deflate over time. In addition to their significant improvement in the prevention of PIs, their three adverse effects (high costs, disturbing noise, negative impacts on patient's mobility) make them impractical for medium risk PI prevention scenarios (Ajami & Khaleghi, 2015; Hayn et al., 2015).

- Another innovative solution is "Mepilex Border Flex" (Figure 7) by "Mölnlycke Health Care" which is a multi-layered silicone foam with a repetitive Y-shaped pattern that makes it considerably flexible and extensible. The dressing reduces the risk of facial tissue damage in prone patients by 33% for the forehead and 80% for the chin (Peko et al., 2020).

Previously used “foam doughnut pillows” (e.g. Baxter) are now discouraged by the nurses since the porous foam becomes soiled easily and quickly with wound drainage. An alternative is a gel positioner that is a single-use pillow filled with a fluidised gel designed to distribute pressure and offload bony parts of the body with the optimum PI protection (max pressure 3.62mmHg). Werthman et al. (2019) suggest that constant use and reimplementation of a fluidised gel positioner results in eliminating the occipital pressure ulcers from 9 to 0.

Figure 6

The Active Air 4 APAM overlay placed on top of a foam mattress.

Note. From *Dynamic Mattress Overlay* by Aspire, 2021 (https://www.aidacare.com.au/products/pressure-care-circulation)

Figure 7

Multiple layers of Mepilex Border Flex designed to stay on and uniquely conform.

Note. From *Mepilex Border Flex* by Mölnlycke, 2021 (https://www.molnlycke.com/products-solutions/mepilex-border-flex/)

Role of Sensors

Since pressure is the ultimate reason behind the PIs, pressure sensors are the most commonly used detectors in monitoring the in-risk areas (Hayn et al., 2015). Sensors are used to measure the amount of pressure, shear force, and stress on the skin and body parts and maximise the effectiveness of the material used in cushion and mattress manufacturing (Murakami, Ishikuro, & Takahashi, 2012).

The main types of pressure sensors widely used in PI monitoring and prevention devices are electric capacitive and resistive sensors that measure the interface pressure by calculating the capacitance or resistance of a deformable sensing component. Disadvantages such as high power consumption, fragility, external noise interference, and slow response are associated with electric sensors. In contrast, optical sensors (e.g. time of flight (ToF) optical sensor) are durable and immune to external noises. Such sensors are used to design an alternating pressure air mattress (APAM) that inflates and deflates the air cells concerning the pressure level (Lee et al., 2019).

Smith et al. (2004) propose an apparatus that employs three types of pressure sensors (optical sensors, weight sensing pads under each wheel of the bed, pressure-sensitive mats) in combination with a vertical accelerometer (attached to the bed's springs) to monitor and detect patient movements. In a similar approach, Zimlichman et al. (2011) mounted "EverOn" (a piezoelectric sensor-based device) underneath the bed to detect mechanical strains and monitor bed movements and activities. Sensors can be embedded in textiles to be less obtrusive, as in "TaxiCare". Chenu et al. (2013) studied the feasibility of "TaxiCare", a fully wireless piezoresistive sensory system embedded in a three-layer washable textile to monitor excessive buttock pressure in wheelchair users. The data from a novel capacitive sensor developed by Murakami et al. (2012) consists of the shear stress and forces on the skin surface and can be used to assess the material used in mattresses' quality and stiffness, and cushions.

A costly combination of wearable sensors, loadcell-based detectors, and mattress-based sensors are used in some monitoring devices to enhances the outcomes (Minteer et al., 2020). Some sensors that are used in wearable devices are as follows:

- Accelerometers for three-dimensional acceleration measurement
- Gyroscopes for three-dimensional angular velocity
- Magnetometers for detecting the direction
- Light sensors for lamination measurement
- Thermometers for measuring ambient temperature
- Pressure sensors

A combination of different sensors in the “eHealth” system measures the relative body position and level of pressure, humidity, and temperature on a sitting mat and displays the real-time results on a smartphone (Sung & Park, 2019)

“Sub-Epidermal Moisture (SEM) Scanner” by “Bruin Biometrics” is a portable wound assessment device that uses integrated electrode sensors to measure changes in the capacitance of skin and tissue water in the presence of an electrical force. The results show subcutaneous tissue damage and make early interventions possible (Raizman, MacNeil, & Rappl, 2018).

Hayn et al. (2015) believe due to high costs, discomfort while used on the mattress, inaccuracy while used under the mattress, and reduced air circulation while used as wearables, application of sensors is limited to laboratories and individualised manufacturing such as adaptive wheelchair cushion or hospital beds.

Opportunities

Reviewing the literature on “the role of sensors in monitoring and preventing PIs” revealed that quite a few devices use various types of sensors (mainly pressure sensors) to monitor the development of PIs. However, only a few products effectively apply preventative solution without human intervention. Considering the challenge in repositioning the ICU patients especially the prone ones, and with regards to current technological advancements in sensors, 3D scanners, additive manufacturing, and custom-made products, further research on the following topic and questions are recommended:

- Application of sensor systems to facilitate the custom manufacturing of facial support surfaces.

- How to use sensors to measure the pressure on different parts of the face of a prone patient?

- How to evenly distribute head weight on an individualised custom-made support surface with the help of sensors?

- Can flexible 3D printed structures replace or enhance traditional facial support surfaces?

Summary

Pressure injuries are skin and underlying tissue damages in patients with limited or no mobility caused by prolonged exposure to centralised pressure points that exceed 16-33mmHg. Oedema, high or low BMI, and decreased nutritional intake are general risk factors of PIs. Critically ill patients in intensive care units -especially in prone position- are more susceptible to developing PIs due to lack of mobility and malnutrition. Also, preventing PI is not considered high priority in the life-threatening situations, managed in ICUs.

PIs are costly and contribute to morbidity, longer hospital stays and decreased quality of life. Braden and Norton Scales and Waterlow Score are amongst the oldest and most used PI preventive assessment tools in hospitals. Some enhanced assessment scales accurately predict the risk of PIs in patients; nonetheless, the total elimination/prevention of PIs is still a challenge because it heavily relies on the labour-intensive task of repositioning the patient or relocating the support surfaces; and it gets more challenging when it comes to repositioning the head of a prone patient. Another reason is that many assessment tools do not consider frequently used medical devices that apply pressure on the skin.

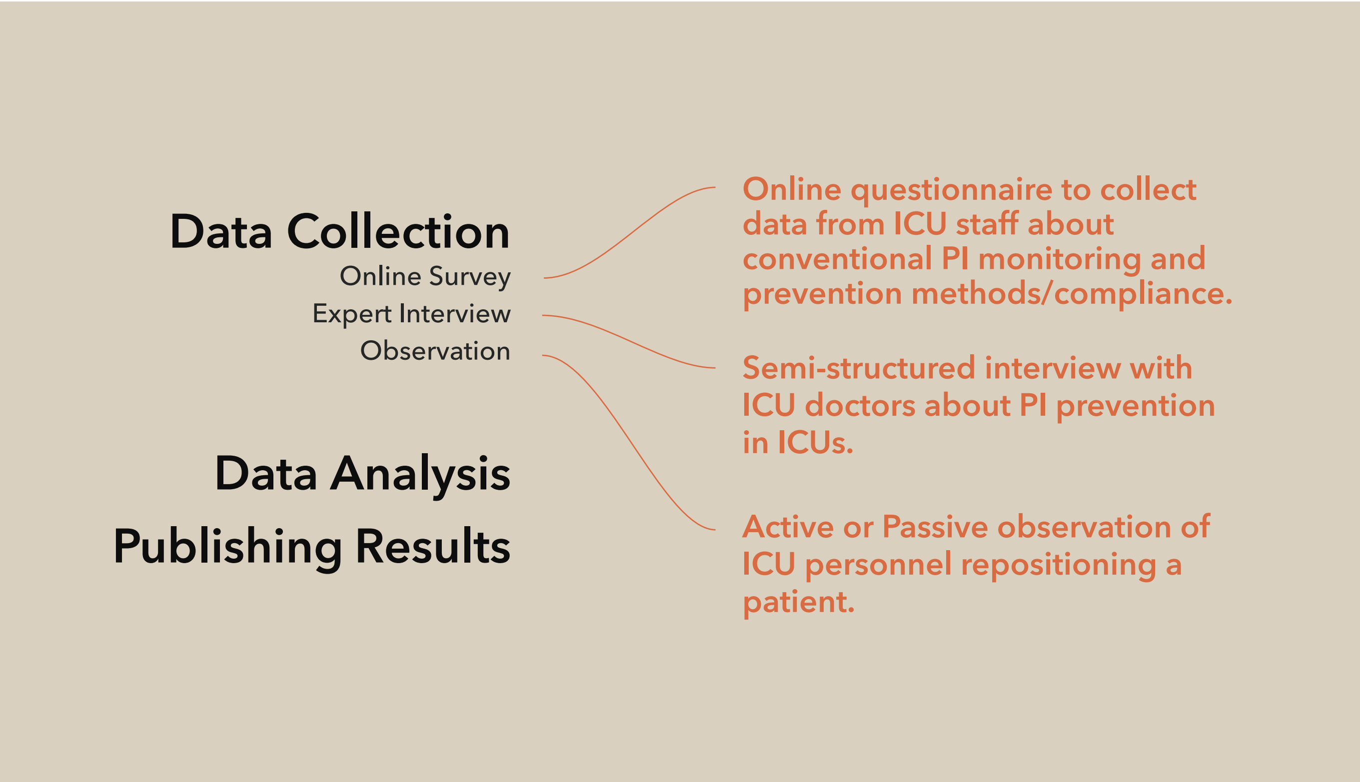
Electronic monitoring systems can provide constant pressure check and share valuable data with doctors, nurses and caregivers. Sensor-based devices have improved the monitoring of PI development and some of them has been integrated with conventional ICU devices and display bed motions besides pulse and respiration rate on their monitors. However, only a few studies have reported experimental results, and clinical trials on sensor-based preventive products/solutions and no studies were found to support the use of sensor systems in design and development of customised or individualised PI preventive products.

Pressure sensors (electric and optical) are the most frequent sensors used in developing pressure monitoring and prevention devices. Most monitoring solutions have sensors on or under mats or mattresses that could be obtrusive, unreliable and not durable for long-term clinical use. There was no evidence of sensor systems' use in the designing and development of customised or individualised support surfaces by employing emerging technologies such as additive manufacturing.

CHAPTER III
RESEARCH DESIGN

How Can Sensor Systems Play a Role in the Monitoring and Prevention of Pressure Injuries in ICU Patients?

Figure 8
Research design structure overview.



A review of the existing literature highlighted a gap in sensors' role in monitoring and preventing PI in ICU patients. While the main question remains as: "How can sensor systems play a role in the monitoring and prevention of facial pressure injuries in ICU patients?", the following sub-questions help narrow the research to focus on the use of sensors in combination with emerging technologies to design individualised support surfaces. Figure 8 illustrates the primary data collection methods.

- How to use sensors to measure the pressure on different parts of the face of a prone patient?

- How to evenly distribute head weight on an individualised custom-made support surface with the help of sensors?

- Can flexible 3D printed structures replace or enhance traditional facial support surfaces?

To obtain a comprehensive understanding of the research topic and identify probable gaps, the researcher conducted secondary methods of data collection by rigorously reviewing the existing literature in the first phase. In the next phase and in order to achieve focused and refined responses to form a concept solution, mixed methods of primary data collection in the form of questionnaire, interview, and observation will be required. Both phases are explained in the following sections.

Systematic Literature Review

In the beginning, relevant keywords have been identified in the Medical Subject Headings Database (MeSH) to explore the possible outcomes around three major concepts: monitoring and preventing pressure injuries, intensive care unit, and sensors. MeSH terms used are listed below:

- ("Pressure Ulcer"[MeSH Terms] OR "pressure ulcer*"[Title/Abstract] OR "pressure wound*"[Title/Abstract] OR "pressure injur*"[Title/Abstract] OR "decubitus ulcer*"[Title/Abstract] OR "bedsore*"[Title/Abstract]) AND ("Intensive Care Units"[MeSH Terms] OR "icu"[Text Word] OR "intensive care unit*"[Text Word]) AND ("Micro-Electrical-Mechanical Systems"[MeSH Terms] OR "sensor*"[Text Word] OR "pressure sensor*"[Text Word])

The combined search results from PubMed database on above terms revealed 24 articles in which 21 were in English, peer reviewed, and accessible online. Articles have been exported to a reference manager software (EndNote 20, Clarivate Analytics) and skimmed. Some more references added to the library by backtracking more relevant articles in design and sensor databases using QUT library website. Quick analysis of the literature, helped dividing the contents into 7 essential sections as follows:

- Pressure injury
- Pressure injury in ICU patients
- Significance
- Risk assessment
- Sensor-based monitoring
- PI prevention methods/ products
- Role of sensors

Methodology

The main question that the primary data collection helped to answer is: "How can sensor systems play a role in the monitoring and prevention of facial pressure injuries in ICU patients?". In that regard, a qualitative research method used to decipher narrative and descriptive data about human interventions to monitor and prevent pressure injuries in ICUs and the possibility of using sensors in combination with emerging technologies such as additive manufacturing and 3D scanning.

Questionnaire The first data collection method is a questionnaire that will be distributed among ICU doctors and nurses via an invitation email. A brief introduction of the research, researcher, why the participant has been selected to enter the survey, and a link to an online questionnaire will be provided in the invitation email. The online questionnaire will collect data on the prevalence of the PI preventative methods and their efficiencies through 12 questions which will take approximately 15 minutes to answer. Participants will be from RBWH and/or Mater hospitals in Brisbane and are asked to share the survey link to other eligible participants. (Due to some limitations, this data collection method was omitted).

Interview To ensure the credibility of the data, the second collection method was conducting semi-structured interviews with ICU doctors/nurses. This approach was chosen to keep the interview within the research focus while giving the interviewee the flexibility and courage to engage and elaborate (Roulston, 2019). The questions were focused on the PI preventive measures in ICU setting (Appendix B).

An invitation email sent to selected ICU experts (nurses) and four experts participated in the interview at QUT Kelvin Grove and online zoom sessions. Participants were asked to sign a consent form, because the Interviews were audio recorded. To retrieve high-quality data and categorise the answers, the data was transcribed and codified.

Observation The third data collection method was a passive observation that helped to validate the interview and retrieved accurate and credible data in context. According to DeWalt and DeWalt (2011), exposure to a routine task helps the researcher learn more in depth about the activity and its context.

Literature shows, repositioning the patient in prone mode while different ICU device attachments such as mechanical respiratory tubing or catheters are connected, is a sensitive and labour-intensive task. Observing this task highlighted nurses' pain points and clarified the ambiguities such as body rotation angles or changing/relocating support surfaces. Since this project did not have an ethics approval to observe the real activity in a clinical setting, the observation was conducted in a simulated environment at Herston Biofabrication Institute on a patient simulator mannequin (dummy). During the observation, several ICU nurses repositioned a mechanically ventilated unconscious patient in prone mode.

Schedule

Conducting qualitative research can be a time-consuming process. Since this project's timeframe is limited to an academic semester, a detailed timetable was required for managing the project. The following Gantt chart (Figure 9) represents the tasks and their allocated timeframes.

Figure 9

Estimated timeline for the first two phases of the project.

Conclusion

The project's topic is the role of sensors in monitoring and preventing facial pressure injuries in ICU patients. To construct a research design, the topic then divided into seven subcategories for more clarity and understanding. A thorough literature review has been conducted on each subtopic. The conclusion revealed a series of questions highlighting a gap in the existing studies, which was the limited use of sensor systems to prevent facial pressure injuries and lack of emerging technologies in such solutions.

To address the questions, a primary research strategy has been planned. The data collection conducted in the second phase and included four expert interviews and a pasive observation. The result then analysed in the third phase, and relevant design concepts proposed in the last stage.

The research complied with a detailed timetable and finalised a week before the submission deadline. To align with the assessment requirements, a 2-week online leadership initiative course by Deakin University; and "Leading Projects" online course which is part of the National Association of State Boards of Accountancy (NASBA) learning program completed by the author (Appendix E & F).

CHAPTER IV
ANALYSIS, RESULTS

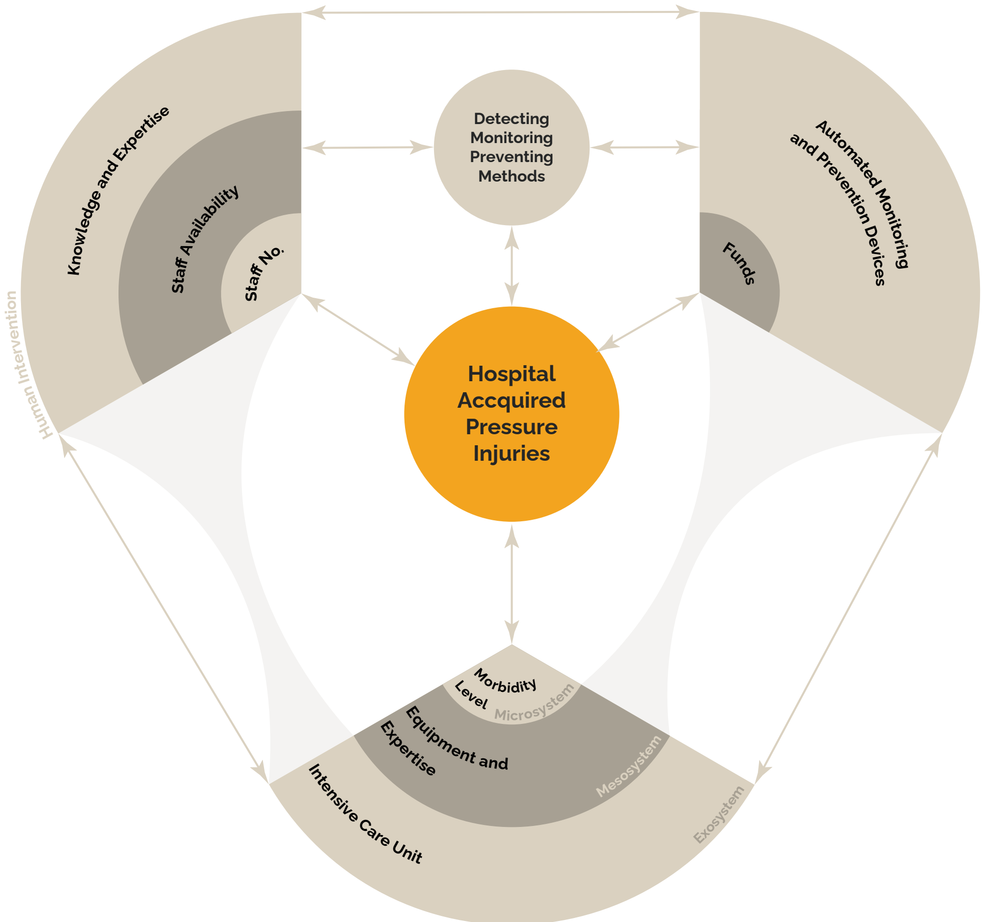
Qualitative Analysis

The analysis focused on four interviews with senior Australian ICU nurses (currently held academic positions) and a pre-recorded video observation of a "patient-repositioning" in a simulated environment narrated and explained by one participant.

From the interview and observation transcriptions, pressure injury-related data (assessment tools, detecting and preventing methods, interventions, body parts, and equipment) were identified and explored using thematic analysis based on Evette's biological, psychological, and interpersonal dynamics theory (Lehman, David, & Gruber, 20W17)(Figure 10). All comments were reviewed to identify categories, and the researcher examined broad themes within each category before secondary thematic analysis. All comments were then coded and reviewed in detail by NVivo 1.5 (QSR International Pty Ltd, 2021). The themes related to the causes and prevention of pressure injuries emerged while building the coding framework (Appendix C) through the analytic process (Appendix D).

Figure 10

Research findings aligned with Evette's biological, psychological, and interpersonal dynamics theory.



Results

All participants agreed that pressure injuries occurred in intensive care units. Half the participants believed the rate is high. One mentioned that according to their experience, “it is not that high”, and one argued that such high numbers were created to “…build on people’s research careers to some degree.”.

Participants only had experience with pressure injuries in intensive care units; however, they are common in aged care facilities too. Assessment tools can effectively predict the risk of pressure injury development in some cases; however, they are not practical in preventing them. Assessment tools are “very broad kind of assessments” and “cannot capture some of the physiological issues encountered in some really unwell patients in terms of problems with microcirculation”. One of the participants argued that assessment tools are not “ICU specific enough”. Also, they do not factor in the complication that is around intubated prone patients.

All patients are assessed for pressure injury risk upon admission because “…healthcare facility is liable for anything that happens in those domains”. Risk assessment tools are among mandatory hospital paperwork; however, in some cases, nurses do an extra inspection on skin integrity to decide the level and frequency of repositioning. Inspection needs to be performed during every repositioning to find the pressure points and decide how they might be alleviated with different means. Sometimes pressure injuries can develop under the wound, so it is helpful to open the bandage and inspect the area. This action depends on the expertise of the nurse.

Some ICUs have handheld digital scanners to measure subepidermal moisture. Other monitoring devices such as continuous pressure mats constantly monitor the pressure points and send repositioning reminder alerts to nurses. Such devices are not readily available due to high cost.

Thematic analysis of contribution factors showed that the following six criteria play a significant role in developing pressure injuries in ICU patients: 1) Immobility because of sedation or severe morbidity. 2) Malnutrition through significant electrolyte anomalies or multiple organ failure. 3) lack of expertise in ICU (such as the capability of removing the wrinkles from under the patient or the capacity to perform organised teamwork). 4) Drugs that shut down a patient’s peripheral vascular system. 5) Devices such as endotracheal and nasal gastric tubes that force pressure in the corner of the mouth and nostrils, respectively, are the major causes of facial pressure injuries in prone patients. 6) A lack of adequate preventative equipment such as appropriate sized pillows, dynamic mattresses or optimal proning devices which can significantly impact the manual respositing of bariatric patients.

The success rate of some of the preventative devices are not evident, and “…a lot of ICUs try to balance the cost of it versus the efficacy of it.”. Cost is another reason for lacking preventative devices: “…the only time I’ve seen those ever used is for research purposes.”.

Thematic analysis of pressure injury patients categorised them in three groups discussed in descending order of frequency: The first group is critically ill with altered perfusion and pathophysiology. In a patient with an unstable airway, preventing pressure injury has a lower priority. Sometimes, chronic comorbidities make repositioning impossible, and sometimes families want to spend more time with their patient. The second group are bariatric patients who need special equipment, and repositioning them is a more labour intensive task and depends on staff availability and expertise. The third group are the elderly, who have frail skin and are susceptible to develop pressure injuries.

Findings showed that pressure injuries develop in both supine and prone patients. Body parts with bony prominences, including sacrum, heel, back of head and elbows, are more susceptible to develop pressure injuries in supine patients. In prone mode: the forehead, eyebrows, shoulders, knees, female breasts, and male genitalia are more prone to grow pressure injuries. However, in mechanically ventilated -prone- patients, which are rising in number because of COVID-19, pressure injuries develop in the corner of the lips and nostrils due to contact with endotracheal and nasal gastric tubes which are hard to adjust.

Preventing the development of pressure injuries are categorised into two major themes: Dynamic and static. Dynamic methods are primarily used in tier one ICUs. Alternate air pressure mattresses or air cell support overlays have multiple air cells that inflate and deflate, and as a result, redistribute the pressure. For some patients in ICUs, there are beds that tilt and perform a continual lateral rotation therapy. For bariatric patients, rolling machines place them in position or make a quad lateral rotation. There are a few specific devices for prone patients, but not all ICUs accommodate them. Some patients find airflow mattresses very uncomfortable: "…they really hate them", and because of the constants movement "…some can get quite seasick". They start to feel "…like their bottoms sagging, or the legs… even when they're trying to rest.".

Static preventative methods are described as using support surfaces in pressure areas. Hospital pillows, wedges and elastic foams are instances of static support surfaces. Gel surfaces such as Z-flo by Mölnlycke are among the best static surfaces; however, they are single-use and expensive. "…it reduces some of the pressure on [the body part]". Some specific body-part surfaces are used for susceptible areas such as eyes: "…sometimes we use eye pads … and lots of gel to make sure that eyes are lubricated and avoid too much pressure".

For hygienic purposes, hospital pillows are plastic-covered and can cause wrinkles under the patients and speed up the development of pressure injuries. Not all the pillows are adequate to be used as a pressure relief (thin pillows). Wedges widely used in ICUs to alleviate pressure do not have an appropriate cover and increase the risk of pressure injury development.

Human intervention plays a substantial role in both dynamic and static methods because manual repositioning the patient is the best pressure injury prevention method so far. Repositioning a patient is a labour-intensive task that should be done regularly. Depend on various factors; repositioning takes place every 2 to 4 hours. The level of morbidity, body mass and the number of available staff contribute to the repositioning periods.

An experienced ICU staff is needed to assist with endotracheal and other tubings during repositioning the prone patients because "it is an incredible limitation in ICUs that don't have somebody to secure the airway…".

CHAPTER V
DISCUSSION, LIMITATIONS

Discussion

The current study provides information on predicting, monitoring, detecting, and preventing hospital-acquired pressure injuries from ICU staff perspective and explores their methods, solution and expertise in alleviating and eliminating PIs.

Findings revealed that despite most of the existing literature (Santy-Tomlinson & Limbert, 2020; Wåhlin et al., 2020; Werthman et al., 2019), the rate of hospital-acquired pressure injuries might not be that high, and the numbers could be affected by pure research purposes or selection bias. Aligned with what Kottner and Dassen (2010) discussed, findings confirmed that most current assessment tools are broad and not ICU specific; hence nurses' expertise and experience play a significant role in predicting and detecting the risk of pressure injury development. In some tier-one ICUs, nurses use handheld digital devices to inspect moisture build-ups and skin integrity.

Pressure injuries are more common in critically ill and immobile patients. Since in an ICU setting, where patients are mostly fighting for life, preventing pressure injuries does not have a high priority. As Pickham, Berte et al. (2018) also discussed, the risk is higher for older adults and patients with higher body mass index.

Patients in supine mode are susceptible to develop pressure injuries in the back of the head, shoulders, sacrum, and heels. In prone mode, shoulders, female breasts, male genitalia, knees, and various face parts such as forehead and eyebrows are at higher risk. If the patient is mechanically ventilated or intubated, endotracheal tubes and nasal gastric tubes are the reason for developing pressure injuries on the corner of the mouth and nostrils. As Peko et al. (2020) highlighted in their study, this type of pressure injuries is rising in number due to the more mechanically ventilated prone patients of COVID-19.

Automated monitoring and detecting devices are not that common in ICUs. High cost and a lack of success evidence keep hospitals/funding organisations from investing in such devices. However, tier-one ICUs benefit from continuous monitoring systems that send alerts to the ward when repositioning is required. On the other hand, preventative equipment is used widely; an alternate air pressure mattress is one of them. Findings showed that in addition to the earlier discoveries of discomfort from the mattress's noise during inflation and deflation (Ajami & Khaleghi, 2015), patients also complained about the constant movements and resulting nausea.

As earlier discussed by Haesler & Carville (2015), manual repositioning is the best method in preventing pressure injury development. This method is a labour-intensive process and requires cohesive teamwork. To perform a quad or semi lateral rotation, at least five nurses or ward staff should be involved. Usually, the more experienced staff at the top is responsible for rotating the head, especially when the patient is intubated. Repositioning is happening in scheduled intervals between 2 to 6 hours. Depend on the patient's condition; nurses might intervene and perform a rotation during two intervals. Automated inflating wedges are necessary for rotating bariatric patients. Static support surfaces are widely used in hospitals to alleviate pressure. However, not all of them are specifically designed for that purpose and can cause wrinkles under the body that lead to pressure injury. Sometimes, nurses ask occupational therapists to bring their special pillows for occipital pressure zones. Nurses

Repositioning an intubated prone patient is a more complex task and required. The endotracheal or nasal gastric tubes should be in the middle of the mouth and nostrils, respectively, to avoid touching the corner of the lips or nostrils. Pressure injuries on lips and nostrils are common in intubated patients because the area is hard to see and reach while the patient is prone. To avoid pressure on the eyes, eye pads are used with a large amount of lubricants.

Limitations

For this project, a “Passport” contract was signed between Herston Biofabrication Institute (HBI) and QUT; however, due to a lack of appropriate ethics approval, and since HBI is a separate site to Royal Brisbane Women Hospital (RBWH), primary data collection in the form of survey and interview from hospital personnel were not possible. Four experienced nurses who held an academic position with QUT were contacted and interviewed to collect interview data. Collected data may subject to selection bias.

Observing an active repositioning in an ICU setting was impossible since anyone who works in the hospital setting, with or without patients, requires acceptable evidence for specified vaccine-preventable diseases. To collect observation data, a pre-recorded prone patient repositioning in a simulated environment video was used.

CHAPTER VI
PROPOSAL, CONCEPTS

Proposal

The research highlighted that repositioning a critically ill patient in ICU is a labour-intensive task, requires cohesive teamwork and adequate support surfaces. The use of automated PI prevention techniques is not always viable due to cost and some other conditions. Given the proven imposed costs on healthcare systems and the impact of pressure injuries on patient's quality of life, improving and innovating new equipment, techniques, or methods to eliminate the development of pressure injuries in hospitals is crucial.

Design Intent To design/redesign a product or method to entirely or partially prevent the development of pressure injuries on supine or prone patients in the ICU setting.

Justification Automatic pressure injury prevention products are limited to alternate air pressure mattresses, which are not only costly, but they make patients uncomfortable. Static prevention means are usually hospital pillows that have to be covered in plastic due to hygienic protocol, hence making wrinkles under the body. On the other hand, manual repositioning is the only feasible method of preventing pressure injuries that has to perform regularly with at least five experienced nurses. Given all those, a lack of adequate support surface, especially for ventilated prone patients rising in number due to the recent pandemic, worsens the problem.

Context Patients are moved to intensive care units due to their unstable vital signs. Pressure injuries are not life-threatening, and it is reasonable that they do not have a high priority. Making the prevention of PIs automated or hassle-free, could have long term benefits with decreasing the length of hospital stays and costs of pressure injury treatments.

Criteria 1, Environment The final design should function in the intensive care unit environment without interfering with/compromising the functionality of other equipment.

Criteria 2, Function The final design should reduce/eliminate the development of pressure injuries in patients. The design can reduce the procedure length of manual repositioning procedure while maintaining the existing preventative measures, or decrease/eliminate the chance of pressure injury development by regulating the distribution of pressure, or both.

Criteria 3, Feedback The final design should give tactile, audio or visual feedback to enhance the user experience and indicate the proper functionality of the device.

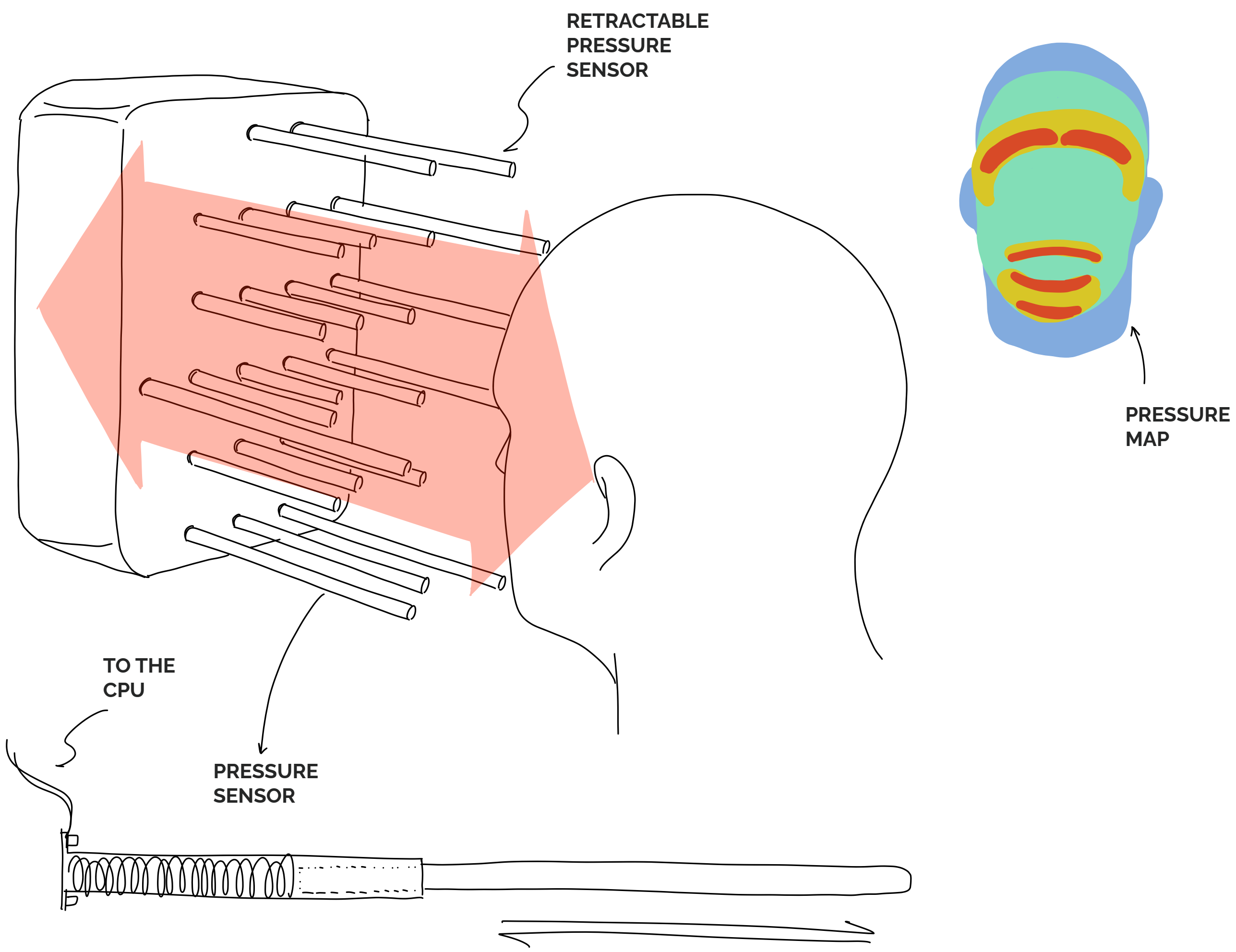
Criteria 4, Material If all or part of the design is in contact with human skin, those parts should be single-use or cleanable. All materials should be compatible with TGA medical device classification system.

Criteria 5, Compliance The final design or solution must comply with Australian regulatory guidelines for medical goods (ARGMG, 2008). Since the final design is medical based, the use of technology must be aligned with the Australian register of therapeutic goods (ARTG, 2013).

Concept I. Pressure Map Generator

Figure 11

Pressure map generator concept. The device uses a series of pressure map sensors to generate a pressure map of the face's sensitive zones.



Problem Facial pressure injuries are very hard to manage in prone patients. Prolonged contact of bony prominences with support surfaces cause PIs in different areas such as the forehead, eyebrows, ears, and cheekbones. Current support surfaces are not efficient since one size does not fit all.

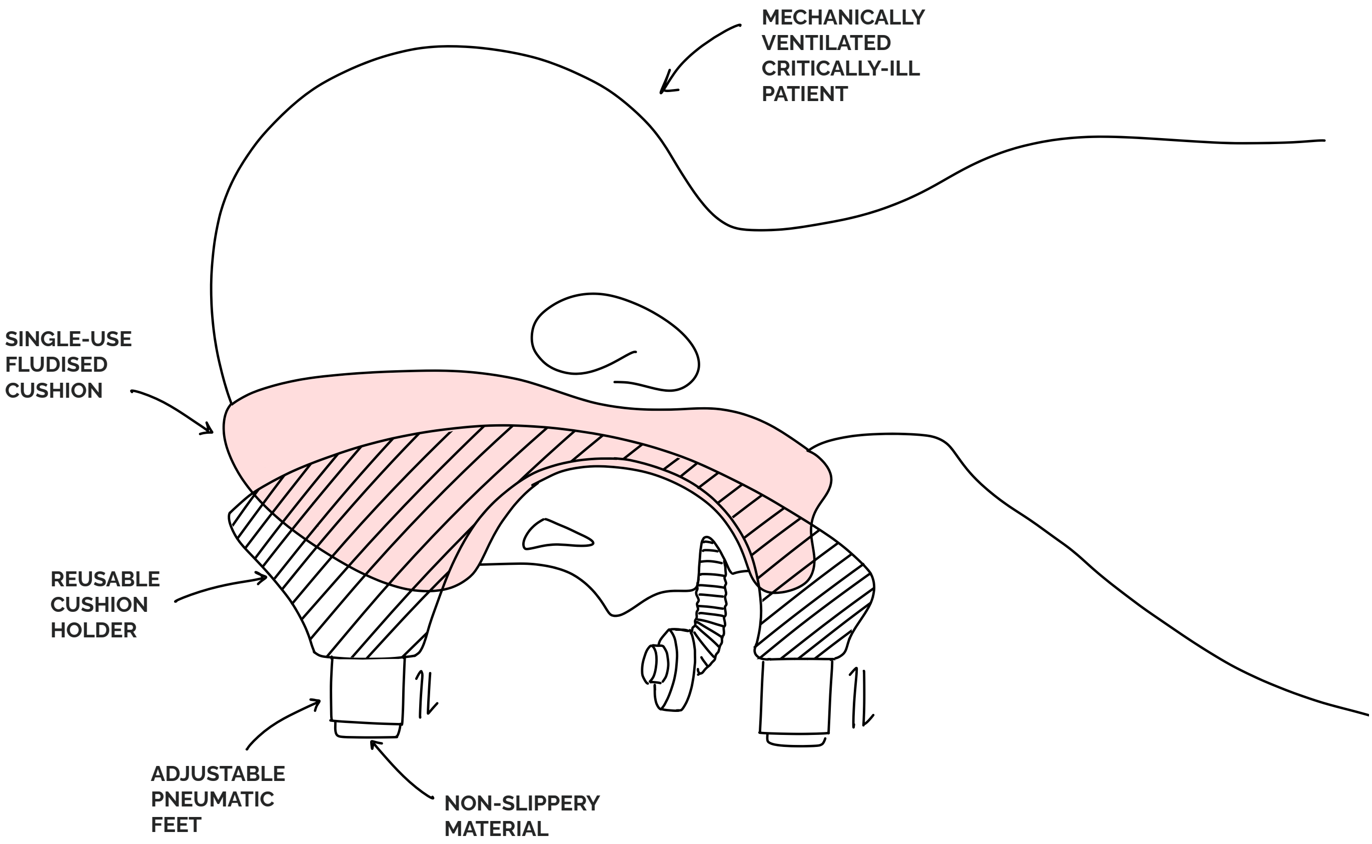
Solution Pressure map generator (Figure 11) is a matrix of pressure sensors that can measure the pressure on an individual's face while faced down on a support surface. Pressure sensors in the form of retractable spring-loaded soft pins arranged in rows and columns and can sense the pressure differentials in different parts of the face. Results are sent to a processing unit, and an individualised pressure map generates.

Pressure maps help design or customise existing support surfaces based on individual needs. Designers can also use the maps to design -or maybe 3D print- pressure alleviating pillows specific to intubated patients, knowing the exact position of mouth and nostrils.

Concept II. Mech-Vent Head Holder

Figure 12

Mech-Vent Head Holder. A prone head holder makes more room to adjust the ventilation tube while protecting the sensitive parts of the head against PIs.



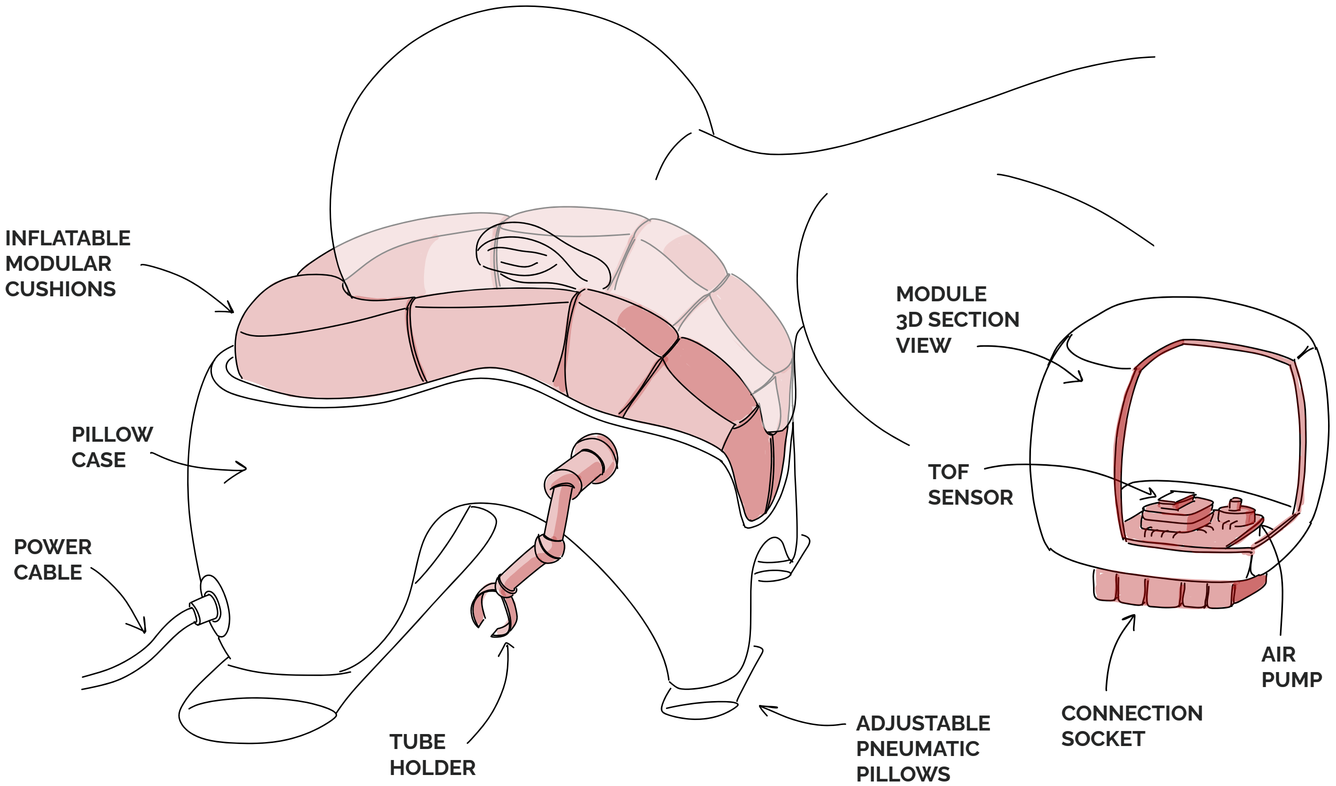
Problem Facial pressure injuries are very hard to manage in prone patients. Prolonged contact of bony prominences with support surfaces cause PIs in different areas such as the forehead, eyebrows, ears, and cheekbones. In mechanically ventilated patients, pressure injuries also develop on the corner of the mouth and nostrils due to the endotracheal and nasal gastric tubes. Adjusting the tubes is a tedious task since the area is hard to see and reach.

Solution The mech-vent patient head holder (Figure 12) is a support device with pneumatically adjustable feet. Single-use fluidised cushions prevent the development of pressure injuries in sensitive bony prominences, while there is enough room to access and adjust the ventilation tub. A mirror can be placed under the device to provide more visibility. The device can be mounted while the patient is in supine mode because the sticky fluidised gel keeps the device in place while rotating the patient. Pneumatic feet adjust the height based on the perceived pressure, so the comfort of the head and neck is not compromised. The only single-use part is the cushion and the rest of the device can be sterilised and hygiene.

Concept III. Modular Alt-Air Head Pillow

Figure 13

The modular alt-air head pillow is a prone patient device that eliminates the development of pressure injuries in ventilated patients. Modules are replaceable, and the endotracheal tube is secured with an adjustable arm.



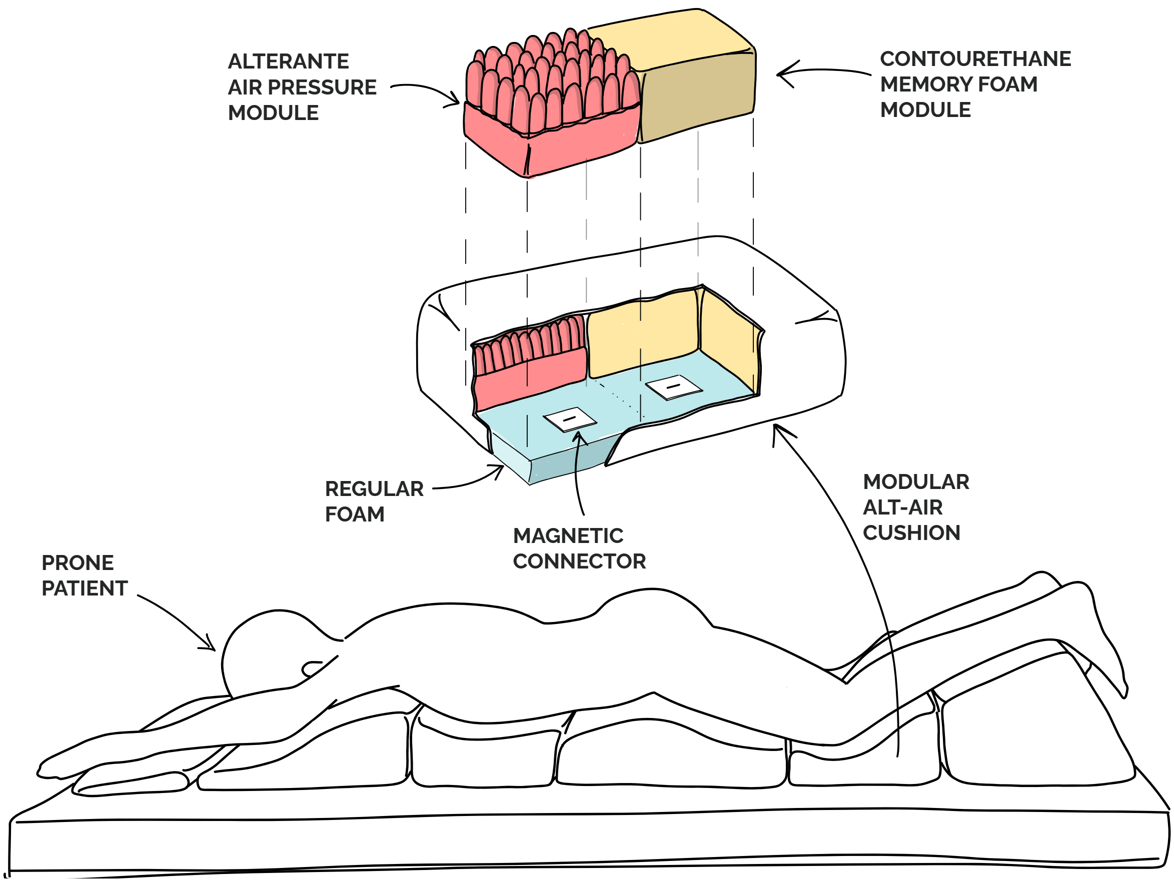
Problem Facial pressure injuries are very hard to manage in prone patients. Prolonged contact of bony prominences with support surfaces cause PIs in different areas such as the forehead, eyebrows, ears, and cheekbones. In mechanically ventilated patients, pressure injuries also develop on the corner of the mouth and nostrils due to the endotracheal and nasal gastric tubes. Adjusting the tubes is a tedious task since the area is hard to see and reach.

Solution The modular alternate air pressure head pillow (Figure 13) is a smart device that eliminated pressure injuries on the face. The cushions that come into contact with the skin are modular inflatable pillows that house a time of flight (TOF) sensor to measure the pressure on the surface. The air pressure adjusts according to the analysed data from the TOF sensor. The modules come in different sizes and can be changed easily to accommodate different head sizes. A robot arm like peripheral holds the ventilation tube in place to avoid contact to the corner of the mouth or nostrils. The device is mounted on a set of pneumatic pillows that adjust the height.

Concept IV. Modular Alt-Air Cushion

Figure 14

The modular alt-air cushion is a redesign of the existing alt-air pressure mattress. The difference is that module cubes in the redesign can be replaced with regular Contourethane foams to reduce cost significantly.



Problem Pressure injuries are hard to manage in prone patients. Prolonged contact of bony prominences with support surfaces cause PIs in different areas such as heels, knees, elbow, female breasts and male genitalia. Alternate air pressure mattresses are expensive and have several drawbacks; manual repositioning is a labour-intensive task that requires at least five ICU staff.

Solution The modular alternate air pressure cushion (Figure 14) is a pillow with replaceable cubes. The base foam is a regular foam with several magnetic connectors in several rows and columns (depending on the size of the cushion). According to the size and weight of the patients, the module can be replaced with Contourethane or alternate air pressure cubes. Contourethane modules conform to the body's shape, while alt-air pressure cubes inflate and deflate to distribute the pressure in sensitive areas. Air pressure is set according to the data of a pressure sensor in the module.

CHAPTER VII
CONCLUSION

Conclusion

Pressure injuries are localised damage to the skin and underlying soft tissue due to persistent pressure on the skin. Critically ill patients in ICUs are more susceptible to develop PIs because of their very limited or no mobility and severe morbidity. The use of additional devices in ICUs to stabilise patient's vital signs adds up to the higher risk of developing PIs. Pressure injuries impose extra costs to the health organisations and impact patient's quality of life.

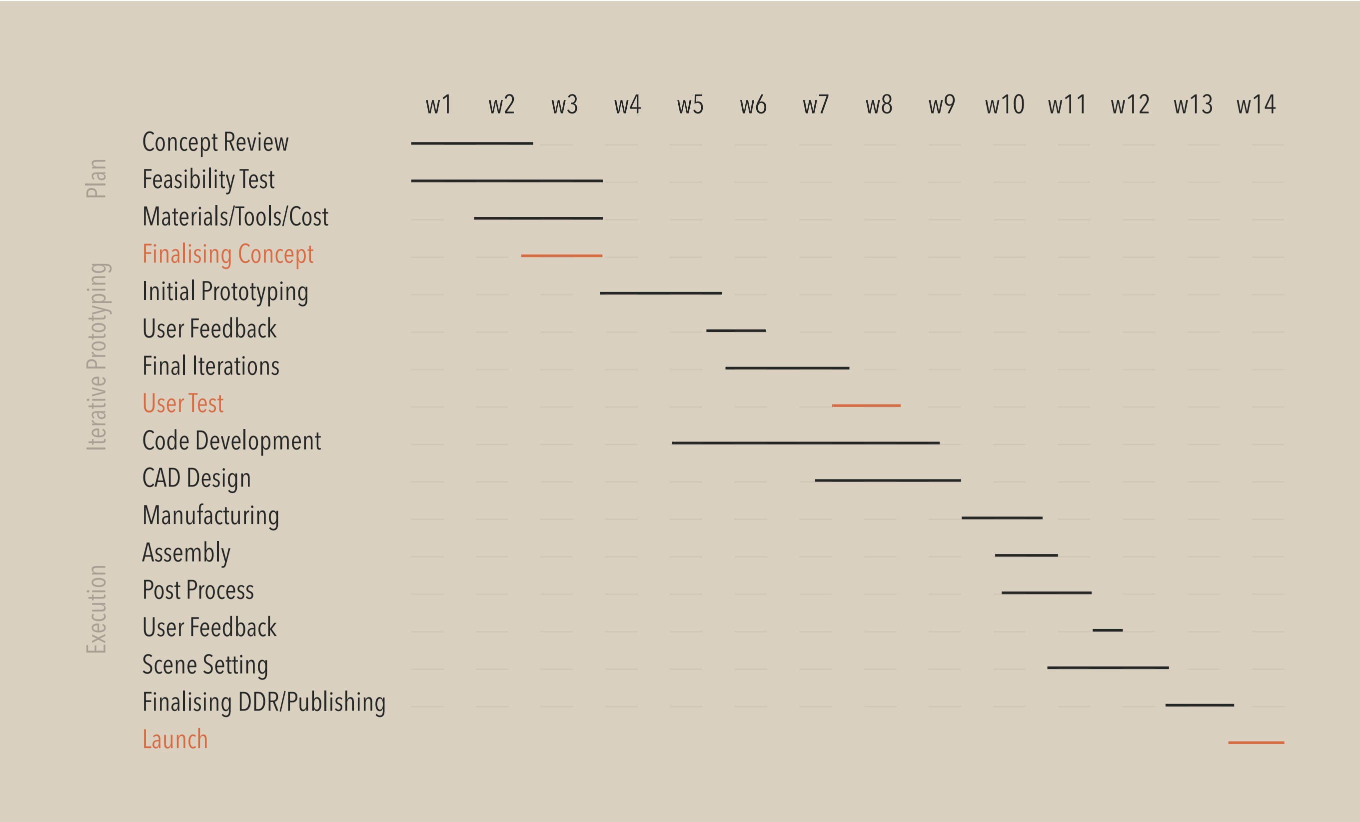
Some predicting procedures (assessment tools) have been developed and enhanced over the years and are used widely in hospitals before patient's admission. Assessment tools can predict the development of pressure injuries in hospitals; however, they are not efficient in an ICU setting where patients are fighting for life. Some digital detecting devices usually employ pressure sensors to constantly monitor patient movements and pressure zones and alert the nurses when necessary. Some costly preventative tools are used in some ICUs; nevertheless, manual repositioning the patient is the optimum way of preventing PIs. Repositioning is the act of manually rotating the patient to some degree and redistribute the pressure on bony prominences. Since the ICU patients are sedated and cannot communicate, manual repositioning is a labour-intensive task, usually involving five nurses or ward staff. Repositioning the intubated prone patients is more complex and requires an experienced ICU nurse to be present and guide the procedure.

The research process in this paper started with a systematic literature review in existing peer reviews articles about detecting and preventing pressure injuries. Findings confirmed that there is a lack of preventative devices with sensors, especially for prone repositing. A series of interviews and observation then conducted to confirm the findings and highlight the gap and needs. Rigorous analysis of the primary data, in addition to the existing literature review, resulted in a design proposal and four design concepts that help to prevent the development of pressure injuries in hospitals indirect (e.g. Alt air mattress/pillow) or indirect ways (e.g. pressure map generator to help to make preventive devices).

Concepts will be discussed in a focus group in July, and multiple prototypes will be made to receive user/expert feedback. The final design will be developed according to the following semester schedule (Figure 15).

Figure 15

Estimated timeline for deisng development in semster 2.



CHAPTER VIII
DESIGN JUSTIFICATION

Pivoting the Design

After developing several "support surface" design concepts to eliminate/reduce the pressure injuries in ICU patients (discussed in chapter VI), and to start the final design process, the researcher examined the concepts with biomedical engineers at Herston Biofabrication Institute (Brisbane, Australia) to find out how to measure the outcomes. They suggested that the efficacy of designs could be assessed to some degree by computer simulations. However, due to the complex nature of soft tissues over bony prominences- which are the main areas of developing PIs, the result would be more accurate from a simulation on the physical human body. At the time of writing this thesis, some products can measure the pressure on almost flat surfaces (e.g. MobileMat by Tekscan, United States), none of them is suitable for measuring the active pressure on complex forms (i.e. human face). As a result, the design-led research pivoted towards a pressure measuring device as a design-aid product to help engineers and designers evaluate their design outcomes more accurately. The following paragraphs further discuss the process and final design.

Pressure mats can measure the single direction pressure on different parts of the body such as knees, shoulders, breasts, etc. However, measuring the active pressure on a human's face while on a pillow (with a couple of tubes running down the mouth and nostrils) is one of the most challenging tasks that such products cannot accomplish. The new design approach is towards replicating the human face with embedded force sensors, so designers and engineers will assess their pillow designs.

La tête, the Face Pressure Measurement

Figure 16
Computer generated image of la tete, the face pressure measuring design-aid.

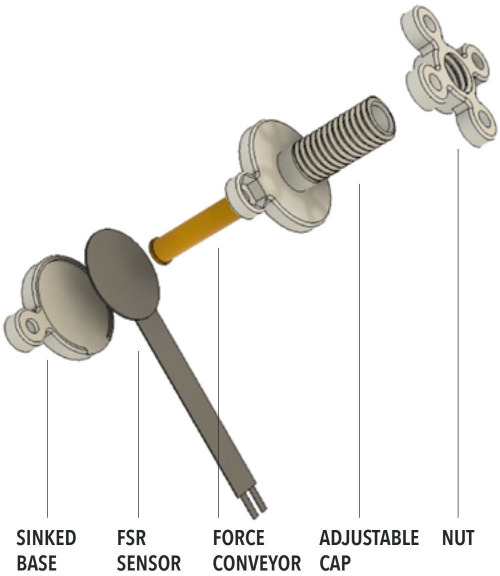


Figure 17
The adjustable 3D printed pressure sensor holder housing exploded view.

The final design (figure 16) is a life-size FDM printed human skull (cut in half on the coronal plane) covered with a polyjet printed skin tissue, all attached to an aluminium stand with the capacity of limited vertical linear movement (to accomodate the support surface or proning pillow). Several pressure sensors are placed in the bone tissue so that they are levelled with the skull surface and right beneath the skin. The adjustable pressure sensor holders (figure 17) are custom designed to convey the skin pressure to the centre of the pressure sensors while holding them in place from inside the skull.

The data from the sensors go to the control unit (via a ribbon cable) and can be viewed live or be stored in a regular SD card to transfer to a computer for further analysis. The control unit is equipped with a capacitive touch screen with a simple and user-friendly interface. The system can record the data from 1 to 24 hours with 5 to 30 minutes intervals.

Current Solutions

Design and manufacturing face support surfaces for proning patients in ICUs has been a great challenge for designers and engineers since there is no device or process to test and validate the product. Figures 18 and 19 show two typical [and not efficient] proning pillows in Australian hospitals. If the hospital does not have access to such simple pillows, the ICU staff use the ordinary pillows or try to avoid proning the patient in the first place.

Figure 18
GentleTouch proning pillow.

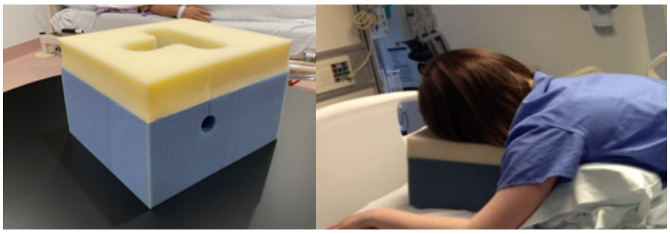


Figure 19
Foam proning support.

Manufacturing

All the necessary files for 3D printing, microcontroller codes, and visual assembly instructions will be available for free on GitHub repository under the name "la tête, face pressure measurement". Note that the overall dimensions of the head sit just under the mean U.S. male (Tilley, 2002), and to design face support surfaces for other groups, the data from respected races should be extracted and interpreted into printable soft and bone tissues.

Limitations

The initial idea of the head was to use the real patient MRI and/or CT DICOM files to build the head. However, since this research was conducted under a general (educational purpose) ethics approval, access to such data could not be approved. The model used for this project is downloaded and then assembled from a public domain website (BodyParts3D, Japan), a comprehensive scientific database of human MRI Anatomography.

Future Potentials

As discussed in earlier chapters, pressure injuries are not limited to intensive care units. Human skin is more susceptible to developing PIs by aging, and this phenomenon is more common among the elderly the more they age, and the less they move. Manufacturing mattresses, cushions, pillows, and support surfaces that distribute the pressure evenly and in the right place will lead to a longer and healthier life. La tête is the first pressure measuring device that addresses the complexity of the human body by developing more accurate sensors and applying the same methods to different parts of the body, this product can expand to a full-size human model and be used as a design aid for measuring the actual pressure from a wheelchair cushion or an aged care facility bed over time.

APPENDICES

Appendix A. PI Risk Assessment Tools

1. Braden Scale

BRADEN SCALE FOR PREDICTING PRESSURE SORE RISK

Patient's Name ______________ Evaluator's Name ______________ Date of Assessment

SENSORY PERCEPTION ability to respond meaningfully to pressure-related discomfort	**1. Completely Limited** Unresponsive (does not moan, flinch, or grasp) to painful stimuli, due to diminished level of consciousness or sedation OR limited ability to feel pain over most of body.	**2. Very Limited** Responds only to painful stimuli. Cannot communicate discomfort except by moaning or restlessness OR has a sensory impairment which limits the ability to feel pain or discomfort over ½ of body.	**3. Slightly Limited** Responds to verbal commands, but cannot always communicate discomfort or the need to be turned OR has some sensory impairment which limits ability to feel pain or discomfort in 1 or 2 extremities.	**4. No Impairment** Responds to verbal commands. Has no sensory deficit which would limit ability to feel or voice pain or discomfort.
MOISTURE degree to which skin is exposed to moisture	**1. Constantly Moist** Skin is kept moist almost constantly by perspiration, urine, etc. Dampness is detected every time patient is moved or turned.	**2. Very Moist** Skin is often, but not always moist. Linen must be changed at least once a shift.	**3. Occasionally Moist** Skin is occasionally moist, requiring an extra linen change approximately once a day.	**4. Rarely Moist** Skin is usually dry, linen only requires changing at routine intervals.
ACTIVITY degree of physical activity	**1. Bedfast** Confined to bed.	**2. Chairfast** Ability to walk severely limited or non-existent. Cannot bear own weight and/or must be assisted into chair or wheelchair.	**3. Walks Occasionally** Walks occasionally during day, but for very short distances, with or without assistance. Spends majority of each shift in bed or chair.	**4. Walks Frequently** Walks outside room at least twice a day and inside room at least once every two hours during waking hours.
MOBILITY ability to change and control body position	**1. Completely Immobile** Does not make even slight changes in body or extremity position without assistance.	**2. Very Limited** Makes occasional slight changes in body or extremity position but unable to make frequent or significant changes independently.	**3. Slightly Limited** Makes frequent though slight changes in body or extremity position independently.	**4. No Limitation** Makes major and frequent changes in position without assistance.
NUTRITION usual food intake pattern	**1. Very Poor** Never eats a complete meal. Rarely eats more than ⅓ of any food offered. Eats 2 servings or less of protein (meat or dairy products) per day. Takes fluids poorly. Does not take a liquid dietary supplement OR is NPO and/or maintained on clear liquids or IVs for more than 5 days.	**2. Probably Inadequate** Rarely eats a complete meal and generally eats only about ½ of any food offered. Protein intake includes only 3 servings of meat or dairy products per day. Occasionally will take a dietary supplement OR receives less than optimum amount of liquid diet or tube feeding.	**3. Adequate** Eats over half of most meals. Eats a total of 4 servings of protein (meat, dairy products) per day. Occasionally will refuse a meal, but will usually take a supplement when offered OR is on a tube feeding or TPN regimen which probably meets most of nutritional needs.	**4. Excellent** Eats most of every meal. Never refuses a meal. Usually eats a total of 4 or more servings of meat and dairy products. Occasionally eats between meals. Does not require supplementation.
FRICTION & SHEAR	**1. Problem** Requires moderate to maximum assistance in moving. Complete lifting without sliding against sheets is impossible. Frequently slides down in bed or chair, requiring frequent repositioning with maximum assistance. Spasticity, contractures or agitation leads to almost constant friction.	**2. Potential Problem** Moves feebly or requires minimum assistance. During a move skin probably slides to some extent against sheets, chair, restraints or other devices. Maintains relatively good position in chair or bed most of the time but occasionally slides down.	**3. No Apparent Problem** Moves in bed and in chair independently and has sufficient muscle strength to lift up completely during move. Maintains good position in bed or chair.	

Total Score

Note. From *Braden Scale for Predicting Pressure Sore Risk* by Government of WA, 2021 (https://ww2.health.wa.gov.au/-/media/Files/Corporate/general-documents/safety/PDF/Bradenscale.pdf)

2. Waterlow Score

Waterlow Chart

Pressure ulcer risk assessment tool

OBSERVATION	BUILD / WEIGHT FOR HEIGHT (BMI)	AVERAGE BMI (20-24.9)			0
		ABOVE AVERAGE BMI (25-29.9)			1
		OBESE BMI >30			2
		BELOW AVERAGE BMI<20			3
	SKIN TYPE VISUAL RISK AREAS	HEALTHY			0
		TISSUE PAPER			1
		DRY			1
		OEDEMATOUS			1
		CLAMMY, PYREXIA			1
		DISCOLOURED (GRADE 1)			2
		BROKEN / SPOTS (GRADE 2-4)			3
	GENDER	MALE			1
		FEMALE			2
	AGE	14-49			1
		50-64			2
		65-74			3
		75-80			4
		80+			5
	MALNUTRITION SCREENING TOOL (MST)	A HAS PATIENT LOST WEIGHT RECENTLY?	YES	GO TO B	-
			NO	GO TO C	-
			UNSURE	GO TO C & SCORE	2
		B WEIGHT LOSS SCORE	0.5 - 5KG		1
			5 - 10KG		2
			10 - 15KG		3
			>15KG		4
			UNSURE		2
		C PATIENT EATING POORLY OR LACK OF APPETITE	NO		0
			YES		1
	CONTINENCE	COMPLETE / CATHETERISED			0
		URINE INCONTINENT			1
		FAECAL INCONTINENT			2
		URINE & FAECAL INCONTINENT			3
	MOBILITY	FULLY MOBILE			0
		RESTLESS / FIDGETY			1
		APATHETIC			2
		RESTRICTED			3
		BEDBOUND E.G. TRACTION			4
		CHAIRBOUND E.G. WHEELCHAIR			5
SPECIAL RISKS	TISSUE MALNUTRITION	TERMINAL CACHEXIA			8
		MULTIPLE ORGAN FAILURE			8
		SINGLE ORGAN FAILURE (RESP, RENAL, CARDIAC)			5
		PERIPHERAL VASCULAR DISEASE			5
		ANAEMIA (HB < 8)			2
		SMOKING			1
	NEUROLOGICAL DEFICIT	DIABETES, MS, CVA			4-6
		MOTOR/SENSORY			4-6
		PARAPLEGIA (MAX OF 6)			4-6
	MAJOR SURGERY OR TRAUMA	ORTHOPAEDIC / SPINAL			5
		ON TABLE > 2 HOURS			5
		ON TABLE > 6 HOURS *			8
	MEDICATION (Max of 4)	CYTOTOXICS			1
		LONG TERM / HIGH DOSE STEROIDS			1
		ANTI-INFLAMMATORY			1
	SCORE TOTAL				

- Ring scores in table, add and total.
- More than 1 score per category can be used.

- Scores can be reduced after 48 hours, provided patient is recovering normally.

© Adapted from Waterlow Risk Score (Waterlow 2005)

SCORE

10+	AT RISK
15+	HIGH RISK
20+	VERY HIGH RISK

Note. From *Waterlow Chart* by Ultimate Healthcare, 2021 (https://www.ultimatehealthcare.co.uk/images/pdf/Ultimate_Pressure_Care_-_Waterlow_Pressure_Ulcer_Risk_Assessment_Tool.pdf)

3. Norton Scale

RCD.9999.0096.0460

The Norton Pressure Sore Risk-Assessment Scale Scoring System

The **Norton Scoring system**, shown below, and created in England in 1962, has been the first pressure sore risk evaluation scale to be created, back in 1962, and for this it is now criticized in the wake of the results of modern research. Its ease of use, however, makes it still widely used today.

To evaluate the Norton Rating for a certain patient look at the tables below and add up the values beside each parameter which apply to the patient. The total sum is the Norton Rating (NR) for that patient and may vary from 20 (minimum risk) to 5 (maximum risk).

(Indicatively, a Norton Rating below 9 means Very High Risk, 10 to 13 means High Risk, 14 to 17 medium risk and above 18 means low risk)

Physical Condition	Good	4
	Fair	3
	Poor	2
	Very Bad	1
Mental Condition	Alert	4
	Apathetic	3
	Confused	2
	Stuporous	1
Activity	Ambulant	4
	Walks with help	3
	Chairbound	2
	Bedfast	1
Mobility	Full	4
	Slightly Impaired	3
	Very Limited	2
	Immobile	1
Incontinence	None	4
	Occasional	3
	Usually Urinary	2
	Urinary and Fecal	1

Generally, the risk factor is coded this way:

Greater than 18	Low Risk
Between 18 and 14	Medium risk
Between 14 and 10	High Risk
Lesser than 10	Very High Risk

Another rating system getting more and more popularity is the **Braden Scale**, created in the USA, more recent and precise than the Norton scale, which evaluates factors such as sensory perception, skin wetness, nutrition and such.

Note. From *The Norton Scoring System* by Royal Commission, 2021 (https://www.ultimatehealthcare.co.uk/images/pdf/Ultimate_Pressure_Care_-_Waterlow_Pressure_Ulcer_Risk_Assessment_Tool.pdf)

4. Risk Assessment Pressure Ulcer Scale (RAPS)

Risk factors	Explanations	Date	Date	Date	Date	Date
Failure in vital organs						
3. Slight						
2. Moderate	Moderate failure in 1-2 organs					
1. Severe	Severe failure, or failure of several organs					
Mobility						
4. Good	Moves self in bed					
3. Somewhat limited	Needs some assistance when changing position					
2. Very limited	Needs complete help with changing position					
1. Immobile	Cannot contribute at all when changing position					
Moisture due to e.g. sweat, urine, or feces						
4. Not at all						
3. Sometimes						
2. Often						
1. Constantly						
Sensory perceptions (related to blockade, sedation, or CNS disease)						
4. Adequate						
3. Slightly impaired						
2. Very impaired						
1. Absent						
Special treatment in form of ventilator, Dialysis, and/or inotropic drugs						
4. None of these						
3. One of these						
2. Two of these						
1. Three of these						
Level of consciousness 4. Fully awake 3. Drowsy but responsive to talk 2. Very drowsy but responsive to pain 1. Unconscious, no response to pain						
Total score						

Note. From *Final version of the Risk Assessment Pressure Injury Scale; RAPS-ICU. Proposed cut-off values are total score ≤18 = increased risk, total score ≤ 15 = high risk, and total score ≤11 = very high risk for pressure injury* by Scandinavian Journal of Caring Science, 2020 (https://onlinelibrary.wiley.com/doi/pdf/10.1111/scs.12891)

Appendix B. Interview Questions

- There is a lot of predictive assessment tools to prevent PIs, why do you think the rate is so high? (1 in 5)

- What sort of support surfaces do you usually use for supine patients? How about prone patients? How do you rate the usability of each?

- While there is a large number of PI monitoring devices, there is just a few and very expensive preventative products (e.g. APAMs); why do you think is that?

- How do you manage the PI preventative measures? I know there are a lot of instructions and requirements; but is it possible to check all the boxes in an ICU setting?

- Is there any specific product or method that you think needs an improvement?

- Could you walk me through applying preventative measures on a mechanically ventilated patient in ICU?

Appendix C. Codebook

Themes	Description	References
Detection	Detecting/predicting of the development of PIs	9
Assessment Tool	A guide chart to measure the susceptibility of a patient to be influenced by PI	7
100% Practical	As if the assessment tools are practical in preventing PI with no other detecting methods	2
Not Entirely Practical	Should be accompanied by other PI detecting methods.	12
Automated Detection	Digital pressure injury devices	2
Automated Detection\High Cost	Costly detection methods of pressure injuries	6
PI	Pressure Injury	100
PI Cause	Causes of development of pressure injuries	48
Devices	Pressure injury related to devices	25
Drugs	Use of drugs to shut down the blood circulation	2
Expertise	Nurse experience and knowledge	7
Immobility	Impediment to movement	4
Limitation	Equipment or staff limitations	8
Malnutrition	Malnourishment	2
PI Patients	Patients who are susceptible to be influenced by PIs	19
Aged	Aged patients	2
Bariatric	Patients with obesity	3
Critically Ill	Critically ill patients in ICU	11
Immobile	Patients who can't move due to consequences.	3
PI Prevalence	The commonness of HAPI	6
High Rate	High rate of HAPIs	3
Not High Rate	Anything but high rate. E.g. Low, made-up results	3
PI Zones	Parts of the body that are prone to pressure injury	27
Back of Head	Vulnerable body part to pressure injury	1
Elbow	Vulnerable body part to pressure injury	1
Female Breast	Vulnerable body part to pressure injury	1
Forehead	Vulnerable body part to pressure injury	1
Heel	Vulnerable body part to pressure injury	5
Mouth & Lips	Vulnerable body part to pressure injury	6
Nostrils	Vulnerable body part to pressure injury	5
Sacrum	Vulnerable body part to pressure injury	4
Shoulder	Vulnerable body part to pressure injury	3
Places	Places that patients might develop pressure injuries. E.g. ICU, Aged care facilities.	18
Aged Care Facility		1
ICU	Intensive Care Unit	17
Prevention	Preventing the development of PIs	90
Dynamic Methods	Pressure injury preventative devices with automatic application	10
Drwabacks	The features that make dynamic methods less acceptable by clinicians or patients.	3
Expertise	The importance of nurse's knowledge and experience	8
Intervention	Human intervention strategies to prevent the development of PIs	7
Quarted Left Lateral	Tilting the patient less than 90 degrees	1
Labour	An operation that requires more than one person to be completed.	18
Manual Repositioning		12
Hard to adjust	Out of reach areas prone to wrinkles and pressure injuries	7
Repositioning Periods	Periods in which the patient should be shifted	8
Static Methods	Static pressure injury preventative devices/methods	26

Appendix D. Thematic Analysis Sample

Reasearcher 0:00
Thank you so much. So, let's start with the questions. My first question is, there is a lot of predictive assessment tools to prevent PIs. Why do you think the rate is still high?

Participant 1 0:30
I think because an assessment tool is just that, it's a risk assessment tool, it's not a prevention strategy. So it's all well and good to undertake a risk assessment for any condition, pressure injuries being one of those. But your rates are entirely dependent on the intervention strategies you put in place to prevent pressure injuries. So you can do [I hate to be very colloquial] but you can do a risk assessment tool until the cows come home. But it's really what you do about those strategies based on the patient's level of risk that has the utmost impact. rates are high in various areas, certainly aged care, because of the type of population often in residential aged care facilities. You know, patients have frail, they have frail, fragile skin, a lot of them are immobile. So that plays a huge confounding factors to the development of pressure injuries, right. So probably the highest also in intensive care because of the nature of our patient population. They're critically ill, they have altered perfusion and pathophysiology. We give them drugs, [sometimes as a bit of a technical to get the drugs] to, you know, shut down their peripheral vascular system. So circulation to some of their peripheries is closed down a little so we can shunt it to major organs. And that obviously impacts the skin. So you know, we see very large rates of pressure injuries in ICU patients on their sacrum and their heels. And also ICU patients have by far and large, the greatest number of devices to any other patient population. And we do see a lot of injuries related to devices.

Reasearcher 2:06
Great, thank you. My second question is, what sort of support surfaces Do you usually use for supine patients? And also prone patients? And how do you rate the usability of each?

Participant 1 2:24
That might be a bit of a tricky one for me to answer. As in rating the usability. We tend to use either alternating air cell support surfaces, so something like not a foam mattress or a bizarre elastic foam, because that's just a static support. So we use something that's a little bit more dynamic. But it does often depend on the patient's acuity, even in ICU when they're admitted. So in a general Ward, patients would be admitted to a stock standard bed, which is usually a piece of elastic foam. If they're then identified as having a degree of risk for pressure injury development, they would put perhaps an alternating cell overlay over that so that the matress surfaces a little dynamic, that the cells actually fill and decrease with air. So each portion has a cell, so to speak, of the mattress, which goes along the whole bed, and then those would alternate a little to give different sort of levels of support and release. For some patients in ICU, we may actually move to beds that can actually do a tilt, so almost like what we call continual lateral rotation therapy. But we wouldn't do that for pressure injuries, we would actually do that for their lungs, it's a little bit like being on a boat, you can get quite seasick. But you don't rock them very hard. It's very gentle. They go, you know, over about five minutes, they go this way, and then about another five, even half an hour, and it's very gentle. So we tend to standard, I suppose approaches to mattress or to underlying support surfaces for patients and then see what their level of risk is. Obviously, bariatric patients will put on a very large frame. And if we know we're getting a bariatric ones, we have about 300 kilos. And they're wider and longer. Although often you don't need the lengths with bariatric patients, but you certainly need the width.

Reasearcher 5:23
So the third question is, I guess you already covered it in your answers. The question is why there is a large number of PI monitoring devices. But there is just a few and very expensive, preventative products?

Participant 1 5:41
I think the pressure injury monitoring devices is certainly escalating with technology over the last certainly the last decade, and even this century in the 21st century. So what we see now are things like continuous pressure mapping. So you can put that overlay on a patient's bed, and you can to continuously map pressure. And that would perhaps give you a prompt to alter their position. So move them from supine over to, we actually do a quarter left lateral, we don't go for 90 degrees lateral. When we turn patients in ICU, they're sort of like on a quarter turn. So the pressure is shifted, if you like from directly on their sacrum to more on the side of theirs not even on their trunk, enter but more on the back of the buttock. So continuous pressure mapping, they're very expensive. The other thing that's certainly come out is subepidermal moisture scanners that I think Bruin biometrics actually market those I can't remember the company in Australia, but they're in there in Europe. And it's a little handheld device that you hold over the patient's skin cell, the sacrum or on the heel, and it gives you an indication of subepidermal moisture. Now it's not it's an arbitrary value, I think it's done in delta units. It's not a it's not a clinical value, or true indices. But it just gives you an idea. And they sort of say when the range is so between two, four, and two that you haven't got any, like the buildup of moisture, which gives you an indication that perhaps there's a dimmer under the skin which means that the cells are at the junction of the cells are actually could be stretching and we might then be more prone to pressure injury development. So those things sort of coming into play in this country but aren't certainly widely used at all other devices to prevent pressure injuries. I'm trying to think that's probably about the main two that I know. And I think the reason we're still seeing very high rates is because these things are expensive, they're not readily available for clinicians to use the devices idea and I think the evidence is actually still out on the

Note Please refer to the shared folder to access the raw data, complete data analysis of interviews, passive observation, and NVivo project.

Appendix E. Leadership Part A

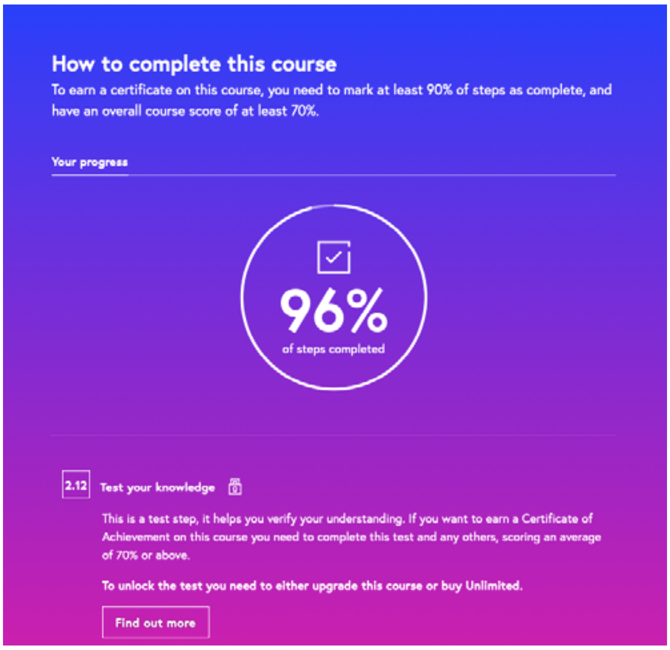
To conduct quality research, better time and resource management, and more meaningful communication with interview and observation participants, the author is participating in Deakin University 2-week online course: What is Leadership (2021) by Future Learn.

The course, which was a combination of lectures, videos and discussions, started with the definition of leadership, continued with the difference between leadership and management and finished with defining various styles of leadership and how they affect work environments. I learned the importance of being curious and aware of different opinions and how to manage bias. The most significant take-out of the course from my perspective was how a leader should make decisions and handle critical situations by paying attention to all the details while being a critical thinker.

There was a video showing two cops investigating three people separately about the murder of their colleague who had an argument with her boss earlier that day. The three people had three different and distinctive opinions about the suspect (the boss) and even remembered different memories from the same event. The lesson was focusing on how prior knowledge can affect our judgment.

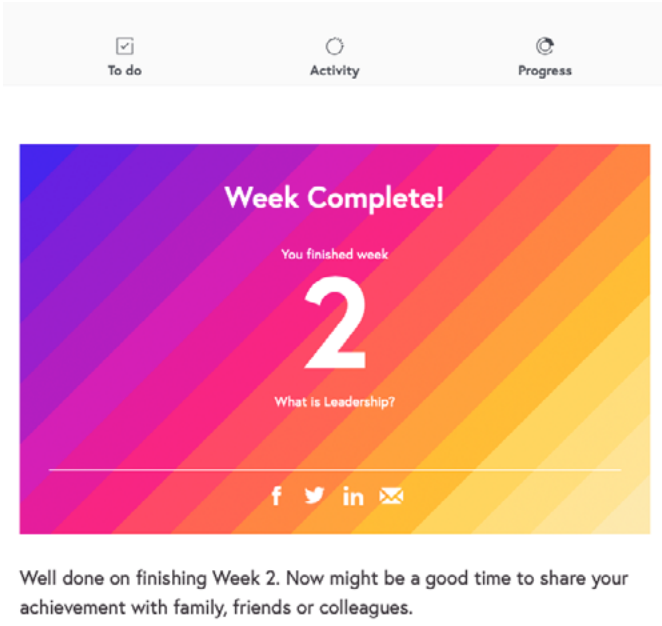
That reminded me of a debate we had earlier in the semester. It was about the relationship between policymaking and innovation. I was in the "affirmative" team, so I started collecting information on how a restrictive policy can stifle innovation (which sounded easy in the beginning because it had not occurred to me that it might be wrong). Very soon, I figured the majority of the literature were in favour of the opposite. So even I was not too fond of the results personally, as a researcher, I had to show both sides of the argument to be able to better support my team. According to Ferguson (2004), leaders are team players who are sensitive, creative, organised, and communicate well, and their power is not linked to their position. In that regard, and to amplify this project's quality, I will employ leadership skill, especially for building trust with my primary research participants and obtaining the most honest data possible.

Course Progress Bar Screenshot



Note. From *How to complete this course* by Future Learn, 2021 (https://www.futurelearn.com/courses/what-is-leadership/7/progress)

Week Completetion Badge Screenshot



Note. From *Week Complete!* by Future Learn, 2021 (https://www.futurelearn.com/courses/what-is-leadership/7/end-of-week/2)

References

Ferguson. (2004). *Leadership Skills*. New York: Infobase Publishing.

What is Leadership. (2021). Future Learn. https://www.futurelearn.com/courses/what-is-leadership/7/todo/103670

Appendix F. Leadership Part B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Continuing Professional Education Credit (CPE): 4.00

The course "Leading Projects" is part of the National Association of State Boards of Accountancy (NASBA) learning program on the role of leadership in managing projects. In this course, I got acquainted with the DIRECT project leadership framework and how to lead cross-functional projects.

Before starting every project, I sit and reverse engineer all project components to develop the best schedule possible. I never hesitate to ask for help to design a better timetable. from my experience, I know that the closer the plan to reality, the more efficient and successful the project. I did the same for this research project, and it would have worked seamlessly in a perfect world. But it did not take long for everything to go wrong. Changes and issues come up along the way, and it is good to be aware, but this time I was bound with many constraints from the university and Herston Biofabrication Institute, and so many things were out of my hand.

Using the six pillars of DIRECT project leadership: Define, Investigate, Resolve, Execute, Change, and Transition, I started investigating possible workarounds and resolving the issues one at a time. Finally, even though I was three weeks behind my schedule, I managed to check all the boxes before the deadline. Changing the new system and managing the transition were the most challenging parts in finalising the project.

REFERENCES

Ajami, S., & Khaleghi, L. (2015). A review on equipped hospital beds with wireless sensor networks for reducing bedsores. *J Res Med Sci, 20*(10), 1007-1015. doi:10.4103/1735-1995.172797

Chenu, O., Vuillerme, N., Bucki, M., Diot, B., Cannard, F., & Payan, Y. (2013). TexiCare: An innovative embedded device for pressure ulcer prevention. Preliminary results with a paraplegic volunteer. *Journal of Tissue Viability, 22*(3), 83-90.

DeWalt, K. M., & DeWalt, B. R. (2011). *Participant observation a guide for fieldworkers* (2nd ed. ed.). Lanham, Md: Rowman & Littlefield.

Efteli, E., & Güneş, Ü. (2020). Assessing the Validity and Reliability of a New Pressure Ulcer Risk Assessment Scale for Patients in Intensive Care Units. *Wound Manag Prev, 66*(2), 24-33. doi:10.25270/wmp.2020.2.2433

Haesler, E., & Carville, K. (2015). Advancing pressure injury prevention around the globe: From the Pan Pacific region to an international pressure injury guideline. *Wound practice & research, 23*(2), 62-69.

Hayn, D., Falgenhauer, M., Morak, J., Wipfler, K., Willner, V., Liebhart, W., & Schreier, G. (2015). An eHealth System for Pressure Ulcer Risk Assessment Based on Accelerometer and Pressure Data. *Journal of Sensors, 2015*, 106537. doi:10.1155/2015/106537

Helfand, M., Christensen, V., & Anderson, J. (2011). VA Evidence Synthesis Program Reports

Technology Assessment: Early Sense for Monitoring Vital Signs in Hospitalized Patients. In *VA Evidence Synthesis Program Evidence Briefs*. Washington (DC): Department of Veterans Affairs (US).

Kottner, J., & Dassen, T. (2010). Pressure ulcer risk assessment in critical care: Interrater reliability and validity studies of the Braden and Waterlow scales and subjective ratings in two intensive care units. *International journal of nursing studies, 47*(6), 671-677. doi:10.1016/j.ijnurstu.2009.11.005

Larcher Caliri, M. H. (2005). Spinal Cord Injury and Pressure Ulcers. *Nursing Clinics, 40*(2), 337-347. doi:10.1016/j.cnur.2004.09.009

Lee, K.-H., Kwon, Y.-E., Lee, H., Lee, Y., Seo, J., Kwon, O., . . . Lee, D. (2019). Active Body Pressure Relief System with Time-of-Flight Optical Pressure Sensors for Pressure Ulcer Prevention. *Sensors (Basel, Switzerland), 19*(18), 3862. doi:10.3390/s19183862

Lehman, B. J., David, D. M., & Gruber, J. A. (2017). Rethinking the biopsychosocial model of health: Understanding health as a dynamic system. *Social and Personality Psychology Compass, 11*(8), e12328. doi:https://doi.org/10.1111/spc3.12328

Minteer, D. M., Simon, P., Taylor, D. P., Jia, W., Li, Y., Sun, M., & Rubin, J. P. (2020). Pressure Ulcer Monitoring Platform-A Prospective, Human Subject Clinical Study to Validate Patient Repositioning Monitoring Device to Prevent Pressure Ulcers. *Adv Wound Care (New Rochelle), 9*(1), 28-33. doi:10.1089/wound.2018.0934

Minton, C., Batten, L., & Huntington, A. (2018). The impact of a prolonged stay in the ICU on patients' fundamental care needs. *Journal of clinical nursing, 27*(11-12), 2300-2310. doi:10.1111/jocn.14184

Murakami, C., Ishikuro, Y., & Takahashi, M. (2012). Feasibility of novel four degrees of freedom capacitive force sensor for skin interface force. *Biomedical engineering online, 11*(1), 1-18.

New technology prevents pressure ulcers. (2011). *Journal of gerontological nursing, 37*(8), 7.

Peko, L., Barakat-Johnson, M., & Gefen, A. (2020). Protecting prone positioned patients from facial pressure ulcers using prophylactic dressings: A timely biomechanical analysis in the context of the COVID-19 pandemic. *International wound journal, 17*(6), 1595-1606. doi:10.1111/iwj.13435

Pickham, D., Berte, N., Pihulic, M., Valdez, A., Mayer, B., & Desai, M. (2018). Effect of a wearable patient sensor on care delivery for preventing pressure injuries in acutely ill adults: A pragmatic randomized clinical trial (LS-HAPI study). *Int J Nurs Stud, 80, 12-19*. doi:10.1016/j.ijnurstu.2017.12.012

Pickham, D., Pihulic, M., Valdez, A., Mayer, B., Duhon, P., & Larson, B. (2018). Pressure Injury Prevention Practices in the Intensive Care Unit: Real-world Data Captured by a Wearable Patient Sensor. *Wounds, 30*(8), 229-234.

Raizman, R., MacNeil, M., & Rappl, L. (2018). Utility of a sensor-based technology to assist in the prevention of pressure ulcers: A clinical comparison. *International wound journal, 15*(6), 1033-1044. doi:10.1111/iwj.12974

Roulston, K. (2019). *Interactional studies of qualitative research interviews*. Amsterdam ;: John Benjamins Publishing Company.

Sakai, K., Sanada, H., Matsui, N., Nakagami, G., Sugama, J., Komiyama, C., & Yahagi, N. (2009). Continuous monitoring of interface pressure distribution in intensive care patients for pressure ulcer prevention. *J Adv Nurs, 65*(4), 809-817. doi:10.1111/j.1365-2648.2008.04935.x

Santy-Tomlinson, J., & Limbert, E. (2020). Using the SSKIN care bundle to prevent pressure ulcers in the intensive care unit. *Nurs Stand, 35*(10), 77-82. doi:10.7748/ns.2020.e11536

Smith, T. E., & Cooper, C. L. (2004). *Apparatus and method for reducing the risk of decubitus ulcers* (6646556).

Sung, C. S., & Park, J. Y. (2019). A monitoring sensor-based eHealth image system for pressure ulcer prevention. *Multimedia tools and applications, 78*(5), 5255-5267. doi:10.1007/s11042-017-4992-3

Tilley, A. R. (2002). The measure of man and woman : human factors in design ([2nd ed]. ed.). New York: Wiley.

Wåhlin, I., Ek, A. C., Lindgren, M., Geijer, S., & Årestedt, K. (2020). Development and validation of an ICU-specific pressure injury risk assessment scale. *Scand J Caring Sci*. doi:10.1111/scs.12891

Werthman, E., Lynch, T., Ware, L., & Caffrey, J. (2019). Evaluating pressure redistribution surfaces for the occiput. *J Wound Care, 28*(Sup9), S38-s41. doi:10.12968/jowc.2019.28.Sup9.S38

Zimlichman, E., Shinar, Z., Rozenblum, R., Levkovich, S., Skiano, S., Szyper-Kravitz, M., . . . Shoenfeld, Y. (2011). Using continuous motion monitoring technology to determine patient's risk for development of pressure ulcers. *Journal of patient safety, 7*(4), 181-184.