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Development of Comforturn: A Smart Mattress System for Automated Patient Repositioning using the 4D Development Model (A Concept Paper)

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ABSTRACT

Pressure ulcers, also known as pressure sores, are a common and preventable complication among mobile patients, resulting from sustained pressure on specific body areas. Manual repositioning is the primary strategy for prevention, but it is physically stressful, time-intensive, and not uniformly performed by care providers. Ripple mattresses provide passive pressure redistribution; however, manual tuning is still necessary and requires an automated approach. This concept paper discusses the design of Comforturn, a smart mattress system capable of automating patient turning with a programmable side tilt and wave-like motion. The goal is to lessen caregivers' work burden and increase patient safety and comfort through combined engineering and clinical approaches. This study is based on the 4D Development Model: Define, Design, Develop, and Deliver. During the Define phase, stakeholder analysis mapped the primary requirements of the nurses and patients. During the design phase, functional specifications and system architecture were developed. A working prototype was established in the Develop stage using Arduino control, and the Comforturn was tested and compared with a ripple mattress in the final Deliver stage. Preliminary findings indicate that Comforturn may significantly reduce the physical burden on caregivers, optimize the ergonomic benefits of turning, and deliver consistent, unbiased turning cycles. Patients could be repositioned more smoothly and comfortably, and caregivers benefited from less manual handling. In conclusion, Comforturn demonstrates the potential of interdisciplinary innovation in preventing pressure ulcers and improving patient care. Integrating technology, engineering, and clinical practice, this system presents a viable solution applicable in hospitals, nursing homes, and home care environments to enhance patient safety and caregiver well-being.

1. Introduction

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Pressure ulcers remain a persistent and preventable complication among immobile patients, caused by prolonged pressure on bony prominences that restricts circulation and damages skin integrity [1]. Manual repositioning every two hours is the current standard of care, yet it is physically demanding, time-consuming, and inconsistently performed due to staffing constraints and competing clinical priorities. The resulting physical strain places nurses at a high risk of musculoskeletal injuries, chronic fatigue, and burnout, ultimately affecting the quality of care and patient safety [2,3]. Existing support devices, such as ripple mattresses, redistribute pressure passively but do not actively reposition patients. As a result, nurses must still perform repeated manual turning, contributing to occupational injuries and limiting efficiency [4,5]. While some smart beds with tilt functions have emerged, most lack adaptive, programmable movement patterns and real-time responsiveness to patient-specific needs [6]. Consequently, the current market offers no fully integrated, nurse-centred solution that addresses both the clinical and ergonomic challenges of repositioning.

This gap underscores the need for an active, intelligent, and customisable repositioning system that can maintain consistent pressure offloading, reduce caregiver burden, and enhance patient comfort without continuous manual intervention. The objective of this research is to design, develop, and evaluate a smart mattress system (Comforturn)that automates patient repositioning using interdisciplinary methods. Comforturn was conceptualised to fulfill this need, integrating programmable side-tilt and wave-like motion with pressure-sensing feedback to deliver adaptive repositioning cycles. Developed using the 4D Development Model (Define, Design, Develop, Deliver) Comforturn combines engineering innovation, sensor technology, and clinical expertise to create a practical, evidence-informed solution.

This is the first smart mattress system to combine programmable side-tilt and wave-like motion with real-time pressure-sensing feedback, delivering fully automated, adaptive repositioning that addresses both clinical efficacy and caregiver ergonomics in a single, integrated platform. With potential applications in hospitals, nursing homes, and home care, Comforturn represents a scalable innovation that can transform repositioning practices, improve patient outcomes, and promote sustainable healthcare delivery.

2. Problem Statement: The Need for Innovation in Patient Repositioning

Pressure ulcers are a prevalent and financially burdensome complication among immobile patients, primarily arising from sustained pressure on susceptible body regions. Although clinical guidelines advocate for repositioning every two hours, inconsistent adherence due to staffing shortages and workload pressures heightens patient risk and extends hospital stays [7,8]. Manual repositioning is one of the most physically demanding tasks in nursing, leading to significant rates of musculoskeletal injuries, such as lower back pain and shoulder strain, affecting over 35% of nurses [5,9]. Current interventions, including ripple mattresses and alternating pressure surfaces, provide passive pressure redistribution but lack active repositioning capabilities, adaptive motion, and responsiveness to patient-specific needs [10,11]. This deficiency not only jeopardises patient safety but also exacerbates caregiver fatigue, disrupts workflow, and diminishes care quality and nurses' satisfaction [12].

Despite pressing clinical and ergonomic demands, there is currently no comprehensive, nurse-centred solution that automates repositioning in a responsive and patient-specific manner [7,13]. Comforturn addresses this unmet need by integrating side-tilt and wave-like motions with pressure-sensing feedback to deliver programmable adaptive repositioning cycles. Preliminary testing indicates its potential to alleviate caregiver strain, enhance ergonomic efficiency, and improve patient safety across hospitals, nursing homes, and home care settings [14,15]. This project aims to develop and evaluate Comforturn, a smart, programmable mattress system that automates patient repositioning through side-tilt and wave-like motions integrated with pressure-sensing feedback. The objective is to reduce caregiver strain, improve ergonomic efficiency, and enhance patient outcomes by delivering consistent and adaptive repositioning cycles suitable for hospital, nursing home, and home care environments.

3. Methodology

This innovation project will employ the 4D Development Model (Define, Design, Develop, Deliver) as a structured framework to guide the conceptualization, prototyping, and evaluation of the Comforturn smart mattress system.

3.1 Define

The Define phase of this project commences with a comprehensive needs assessment aimed at identifying clinical, ergonomic, and technological gaps in current patient repositioning practices. A mixed-methods approach will be employed, integrating a systematic literature review with stakeholder interviews to triangulate findings and ensure contextual relevance. The literature review will encompass about 30 peer-reviewed articles published between 2020 and 2025, sourced from Scopus, PubMed, IEEE Xplore, and ScienceDirect, using keywords such as “pressure ulcer prevention,” “nurse fatigue,” “smart mattress,” and “automated repositioning.” Inclusion criteria focus on studies involving clinical trials, ergonomic assessments, and technological evaluations pertinent to immobile patient care. The review will reveal the significant limitations in manual repositioning practices, the efficacy of ripple mattresses, and the prevalence of nurse-related musculoskeletal injuries, thereby underscoring the need for programmable, sensor-integrated systems. Complementing this, semi-structured interviews will be conducted with around 10 purposively sampled stakeholders, including registered nurses, nursing students, biomedical engineers, and a physiotherapist who are selected for their direct experience with immobile patient care and assistive technologies. Interviews will be conducted both in-person and via Zoom, exploring challenges in manual repositioning, perceptions of existing technologies, desired features in automated systems, and safety concerns. Thematic analysis using NVivo software identified recurring themes such as “physical strain,” “workflow disruption,” “lack of automation,” and “need for adaptive motion.” Collectively, these findings will confirm the absence of an integrated solution that automates patient repositioning while addressing caregiver ergonomics and patient-specific needs. Key design requirements are established, including programmable motion cycles, pressure-sensing responsiveness, and compatibility with diverse care environments, that insights that directly informed the subsequent design phase of the Comforturn system.

3.2 Design

Building upon insights from the Define phase, the Design phase will translate clinical, ergonomic, and technological requirements into a functional blueprint for the Comforturn system. This phase is guided by interdisciplinary collaboration across healthcare, engineering, and ergonomics to ensure that the proposed solution addresses both patient safety and caregiver usability. The Comforturn system is conceptualized to incorporate side-tilt and wave-like motion mechanisms, embedded pressure sensors, and a programmable control interface. Key mechanical features include pneumatic actuators capable of achieving a 30° lateral tilt, replicating manual repositioning angles recommended in clinical guidelines. A motion algorithm will be developed to sequentially inflate air cells, simulating wave-like movement to facilitate tissue offloading and pressure redistribution. Pressure mapping sensors are embedded within the mattress surface to detect high-pressure zones and trigger responsive adjustments. The control system utilizes an Arduino/ESP32 microcontroller, enabling customizable repositioning intervals (15–60 minutes) and incorporating safety overrides. Material selection prioritizes both clinical efficacy and patient comfort, comprising medical-grade PVC for air cells, memory foam for surface cushioning, an aluminum frame for structural integrity, and breathable fabric for hygiene maintenance. Safety features include an emergency stop button, soft side rails to prevent falls, low-noise operation (<40 dB), and a fail-safe mechanism to ensure functionality during power outages. Design validation will be conducted through expert review by two biomedical engineers and one clinical nurse educator, confirming the feasibility and relevance of the proposed specifications. These design elements laid the foundation for prototyping and iterative testing in subsequent phases. The tentative prototype model is shown in Figure 1.

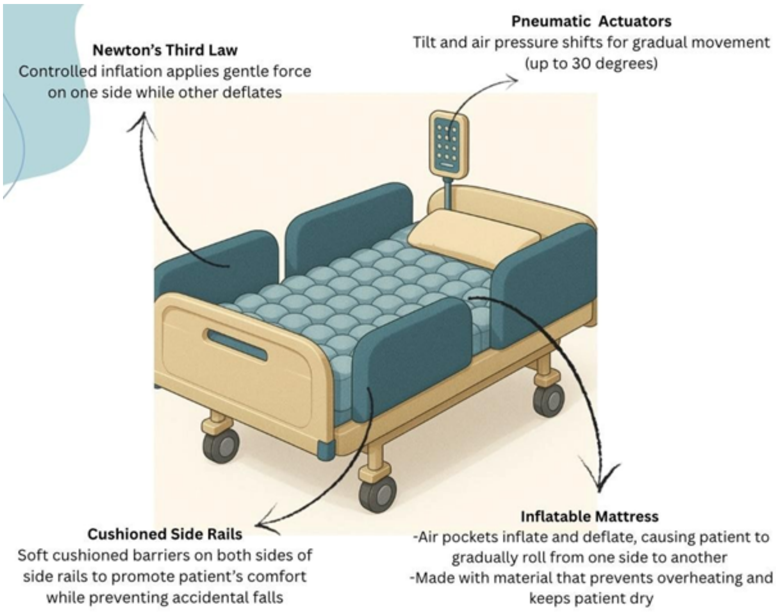

Fig. 1. Prototype model (Comforturn)

3.3 Develop

The Develop phase focuses on constructing and validating a working prototype of the Comforturn system, guided by the approved design specifications. Modular components are employed to facilitate iterative testing and refinement, ensuring adaptability across clinical contexts. Embedded systems are programmed to execute repositioning cycles based on predefined time intervals and real-time pressure distribution feedback. The hardware configuration includes 12V pneumatic actuators, an Arduino Mega 2560 microcontroller with Bluetooth connectivity, FSR402 pressure sensors, an air pump with control valves, and a custom mattress casing featuring modular air cells. Software development utilizes the Arduino IDE to program motion cycles and implement a sensor calibration algorithm for adaptive responsiveness. A beta-version mobile application is also developed to enable remote control and monitoring. Bench testing procedures are conducted to assess motion accuracy, sensor responsiveness, and overall system reliability. Functionality tests evaluate tilt angles, inflation timing, and pressure detection fidelity, while usability assessments by conducted with three nurses and two caregivers using simulated patient mannequins to examine interaction ergonomics and handling requirements. Safety evaluations will address system stability, operational noise levels (<40 dB), and emergency override performance under stress conditions. A preliminary cost analysis estimates the total prototype expenditure at RM6,000, with projections indicating cost reductions in future mass production. These validation activities will confirm the feasibility of Comforturn’s core functionalities and inform refinements for subsequent clinical trials and regulatory review.

3.4 Deliver

The Deliver phase focus on presenting the Comforturn innovation and preparing for pilot implementation through preliminary deployment in simulated care environments. These include mock hospital beds and home care settings designed to replicate real-world conditions. Usability assessments are conducted with nursing staff and caregivers to evaluate comfort, interface intuitiveness, and perceived reduction of physical strain during patient handling. Structured interviews and observational data collection will inform the final refinements to the system’s motion parameters and user interface, ensuring alignment with clinical workflows and ergonomic standards. Presentation materials will be developed for stakeholder engagement, including comprehensive technical documentation, a slide deck detailing the design rationale and testing outcomes, a video demonstration of the prototype in operation, and a comparative analysis highlighting improvements over conventional ripple mattress systems. An implementation plan is formulated, encompassing a pilot trial at the IIUM Teaching Hospital, a training module for nursing staff, and a feedback mechanism to support iterative refinement. Additionally, commercialization pathways are explored in collaboration with the university’s innovation office, including intellectual property protection and production scalability analysis. These activities position the Comforturn for transition from prototype to clinical application, reinforcing its potential to enhance patient care and reduce the caregiver burden.

4. Expected Results and Implications

The Comforturn system is projected to yield substantial advancements in the clinical, ergonomic, and sustainability domains. By automating patient repositioning tasks, the caregiver workload can be significantly alleviated, and the incidence of musculoskeletal injuries among nursing staff can be reduced. The incorporation of adaptive pressure relief mechanisms, facilitated through wave-like motion and embedded sensors, aims to enhance patient safety and comfort, particularly for individuals at an elevated risk of pressure ulcers. The utilization of breathable, medical-grade materials further contributes to patient well-being while supporting hygienic care. From a sustainability perspective, the system integrates durable and reusable components, thereby promoting long-term cost-effectiveness and environmental responsibility. Notably, Comforturn exemplifies the convergence of engineering and digital health in advancing nursing practice and fostering interdisciplinary innovation in clinical settings. This initiative aligns with the core principles of Malaysia Madani, particularly its commitment to compassionate, efficient, and technologically empowered healthcare delivery. Furthermore, it supports the United Nations Sustainable Development Goals (SDGs), specifically SDG 3 (Good Health and Well-being) by improving care outcomes and SDG 9 (Industry, Innovation, and Infrastructure) through the development of scalable, locally relevant health technologies. These implications highlight Comforturn's potential to significantly contribute to both national healthcare transformation and global health innovations.

4. Conclusion

Comforturn represents a significant advancement in nursing care, addressing the persistent challenges associated with manual patient repositioning through an integrated and interdisciplinary approach. Developed using the 4D Development Model (Define, Design, Develop, Deliver), the system synthesizes clinical insights, ergonomic principles, and engineering innovations to produce a solution that is both effective and scalable. By automating repositioning tasks, enhancing patient comfort, and reducing caregiver strain, Comforturn has the potential to significantly improve care quality and operational efficiency in diverse healthcare environments. This concept paper articulates the rationale, design methodology, prototype development, and anticipated outcomes of the system, laying a foundation for pilot implementation and iterative refinement. It invites collaboration across clinical, academic, and industrial domains to validate, optimize, and scale innovations for broader adoption. In doing so, Comforturn not only advances nursing practice but also contributes to the national and global agenda for compassionate and technology-enabled healthcare.

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