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Interventions on Clinical Utility

Development and Evaluation of an Automated Repositioning Bed for Enhanced Patient and Caregiver Support

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ABSTRACT

Background: Automated patient repositioning systems prevent pressure ulcers and support respiratory and circulatory functions in bedridden patients. They enhance patient comfort, improve quality of life, and reduce caregiver burden by minimizing the risks associated with manual handling. This study presents the design and development of a low-cost patient repositioning system with customizable positioning and timing features tailored to patient and caregiver needs.

Methods: We designed the simulated model of an automated repositioning bed, developed its working hardware prototype, and obtained end-user feedback on its usability. The prototype was evaluated for structural integrity using finite element analysis (Young's modulus = 200 GPa, Poisson's ratio = 0.3). A control algorithm was implemented to enable operation while ensuring safety. The electronic circuitry was designed to regulate sensors and actuators through a feedback loop. The system's usability and effectiveness in reducing caregiver workload were assessed based on Likert scale questionnaire feedback from 14 patients and 11 caregivers.

Results: A working design of the prototype bed is developed which implements head, side, and foot movements. The control system utilizes 3 DC motors. The patient load simulation performed on the design showed a small deformation effect with a maximum of 0.54 mm. All participants found the hardware prototype of the system to be capable of reducing caregivers' physical effort required for repositioning. However, the system might not provide patients complete independence for side turning.

Conclusion: This study showcases the viability of a cost-effective patient repositioning system, designed using locally readily accessible materials. Moreover, it addresses a critical need for accessible and practical repositioning solutions that could significantly improve patient care and ease caregiver burden.

Keywords: *Back Injuries, Equipment Design, Moving and Lifting Patients, Musculoskeletal Diseases, Occupational Health Nursing.*

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INTRODUCTION

Patient repositioning is a fundamental aspect of care for bedridden individuals, involving periodic adjustments to their posture to alleviate pressure on specific body areas[1]. This practice is essential for preventing pressure ulcers (bedsores), which develop due to prolonged pressure on the skin and underlying tissues[2].

Beyond pressure relief, regular repositioning helps prevent musculoskeletal complications such as contractures and muscle atrophy, which arise when patients remain in static positions for extended periods[3-4]. Additionally, repositioning enhances respiratory and circulatory function by promoting lung expansion and improving blood circulation, thereby reducing the risk of conditions such as pneumonia[5].

Traditionally, patient repositioning is performed manually by the caregivers or healthcare

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providers[6-7]. While effective, manual repositioning presents several challenges[8]. Patients may experience discomfort, skin tears, bruising, or muscle strain, particularly if they have preexisting frailty or medical conditions[9]. Moreover, inadequate or infrequent repositioning increases the likelihood of developing pressure ulcers[10].

For caregivers, the physical demands of manual repositioning pose significant occupational risks, including musculoskeletal injuries such as strains, sprains, and chronic back pain[11]. Additionally, manual handling techniques can be inconsistent, leading to repositioning frequency and effectiveness variations[12]. Furthermore, there is an inherent risk of falls or accidental injuries during repositioning, which can have severe consequences for patient safety[13]. These challenges underscore the need for safer, more efficient repositioning solutions.

Automated patient repositioning systems have emerged as a viable alternative to manual handling, offering motorized adjustments that improve patient comfort and caregiver efficiency[14-15]. Several commercial systems, such as the Arjo TurnAid, Hill-Rom TotalCare Bariatric Plus Bed, and LINET Eleganza bed, integrate advanced features, including motorized lateral rotation, pressure redistribution, programmable positioning, and movement monitoring. These technologies help reduce caregiver workload, enhance patient comfort, and mitigate the risks associated with prolonged immobility. However, these advanced systems are often prohibitively expensive, making them inaccessible to many of the population, particularly in low- and lower-middle-income countries. The absence of a comprehensive healthcare insurance system in countries like Pakistan limits the affordability and widespread adoption of such assistive technologies[16]. Given these limitations, there is a clear need for an affordable automated patient repositioning solution that can provide essential functionalities without the high financial burden.

This study addresses this gap by designing and developing a low-cost automated patient repositioning system with customizable positioning and timing features to enhance patient comfort and reduce caregiver strain. The system's structural integrity was evaluated through simulation testing using finite element analysis, and a control algorithm was implemented for safety and adaptability. Moreover, usability and effectiveness were assessed through feedback from patients and their caregivers.

METHODOLOGY

Prototype Design and Structural Strength

The 3D design of the patient bed was created using SolidWorks (Dassault Systèmes, Massachusetts, USA). The design comprises two main parts divided into five sections (Figure 1a). The upper part includes four sections: two horizontal sections for head-side elevation and two vertical sections for lateral tilting. The lower part consists of a single section for foot-side elevation. All sections are mounted on a fixed bed frame with four stationary legs (Figure 1b).

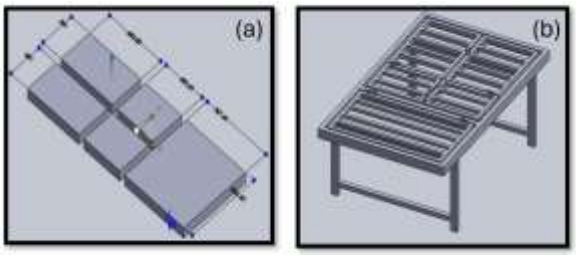

Figure 1. The design of the prototype patient bed is as follows: (a) a bed platform comprising six sections, including upper and lower parts; (b) a bed structure comprising of the bed frame, six sections, and legs;

The strength analysis was conducted using the finite element analysis software ANSYS (Ansys Inc., Pennsylvania, USA). A static structural simulation was performed to evaluate the impact of stress loading conditions on the 3D model of the patient bed, allowing for the identification of potential weak points before hardware implementation. To ensure accuracy, stainless steel was selected as the material, with engineering properties of Young's modulus = 200 GPa and Poisson's ratio = 0.3.

Control Algorithm and Schematic Design

The bed frame is equipped with three 24-volt DC motors, with specifications detailed in Table 1. M1 controls head movement, M2 controls foot movement, and M3 facilitates right and left lateral tilting.

Table 1. Specifications of DC motor

Parameter	Value
Speed	3350 RPM
Voltage	24 V (DC)
Nominal Current	4.9 A
Power	100 W
Torque	0.27 N.m
Net Weight	2.7 kg
Radius	0.325 m

The setup includes eight limit switches and a circuit board, with user control facilitated through push buttons and an LCD on the main circuit board. Limit switches are strategically placed at two key positions for each of the four movements: the zero position (flat, 0-degree angle) and the maximum angle position of the bed. Initially, all four zero-position limit switches must be pressed to confirm that the bed is at the zero position.

Pressing the push buttons sends input signals to activate M1 or M2 for head or foot movement or M3 for lateral tilt. An Arduino Nano controls relays in an H-bridge circuit, driving the selected motor. As the motor rotates, the bed adjusts from the zero position to the desired angle. The corresponding limit switch is triggered upon reaching the maximum angle, signalling the Arduino to deactivate the H-bridge and stop the motor.

The user presses the designated push button to return the bed to its original position, reversing the motor's direction until the zero position is reached, as indicated by the limit switches. This design ensures smooth, controlled, and user-friendly bed adjustments. The complete control flow of the prototype is illustrated in Figure 2.

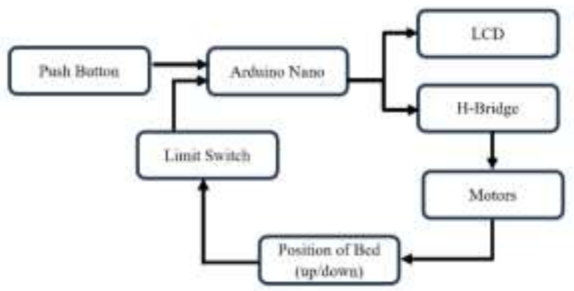

Figure 2. Flow diagram for the control of prototype.

Figure 3a presents the control circuit schematic, where power is supplied by a battery bank consisting of two sets of six lithium cells connected in series and then in parallel with the power supply circuit. This circuit includes charging capabilities through a diode, switch, and LM7812 voltage regulator, ensuring stable voltage management. The power supply feeds the H-Bridge Control Circuit, which integrates an Arduino Nano, an LCD, an optocoupler, and limit switches. These components enable safe and efficient bidirectional control of the DC motor while providing electrical isolation from high-power elements, minimizing voltage spikes and noise to enhance the system's reliability and longevity.

Figure 3b illustrates the system's circuitry and user interface. The LCDs have a "please wait" message when powered on, indicating system initialization. Users interact with the device using four push buttons. In manual mode, button 1 raises the leg and head sections, while button 2 lowers them. In automatic mode, these buttons adjust the time settings—button 1 increases time, and button 2 decreases it, with button 3 saving the set time in seconds. By default, the system operates in manual mode and switches to automatic mode with a long press of button 4. Button 4 also serves as a motor selector: a single press selects motor 1 (M1), a double press selects motor 2 (M2), and a triple press selects motor 3 (M3). This intuitive control layout ensures efficient and user-friendly operation of the bed's functions.

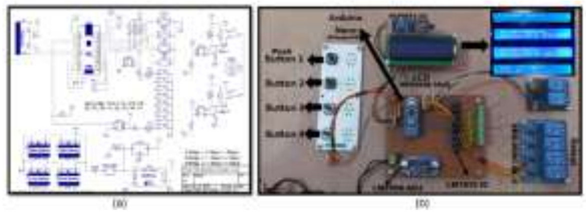

Figure 3. The (a) schematic diagram and (b) overall control circuitry of the prototype comprise a controller, relays, LCD, control buttons, and power adapter.

Feedback from Patients and Caregivers

Patients and caregivers were approached at a rehabilitation and assistive devices exhibition held at the NED University LEJ campus located in Karachi in December 2022. Informed consent was obtained before collecting feedback from the participants.

The prototype was presented to 14 patients and 11 caregivers to assess its usability and effectiveness. The objective was to gather their perceptions of the device's potential benefits for individuals who are bedridden and unable to reposition themselves without assistance. Feedback was collected using a structured questionnaire that included three sections: prototype evaluation, challenges patients face in daily activities, and suggestions for additional features.

Participants rated their responses on a Likert scale (1 = not at all, 5 = extremely) for the following questions:

- Q1. Does the patient's health limit their ability to reposition themselves in bed?

- Q2. Does the caregiver face difficulty when repositioning the patient?
- Q3. Can this prototype assist patients in self-repositioning?
- Q4. Can this prototype ease the caregiver's burden of repositioning?
- Q5. Would you like to have the automated repositioning bed at home?

The data collected from the structured questionnaire was analyzed using descriptive statistics. Each participant's responses on the Likert scale (1 to 5) were averaged to determine the overall perception of the prototype's usability and effectiveness. The responses were grouped by question to assess trends and patterns in patient and caregiver feedback. In addition to the quantitative analysis of the Likert scale ratings, qualitative feedback from open-ended questions (such as suggestions for additional features) was analyzed thematically to identify common recommendations and insights. This combined approach allowed for a comprehensive understanding of the prototype's potential benefits and areas for improvement, as perceived by the patients and caregivers.

Results

Participant Demographics and Feedback

The demographics of patients and caregivers are presented in Table 2. The average age of patients and caregivers was 37.9 and 41.4 years, with standard deviations of 13.9 and 7.5 years, respectively. The majority of patients were diagnosed with muscular dystrophy, followed by polio. Among the respondents, 14% of patients and 27% of caregivers were female.

Table 2. Patient and caregiver demographics.

Sr #	Role	Gender	Age (years)	Disease
P1	Patient	Male	31	Polio
P2		Male	33	Polio
P3		Male	45	Polio
P4		Male	28	Polio
P5		Female	21	Carcinoma
P6		Male	70	Motor neuron disease
P7		Female	30	Amputee from both legs
P8		Male	26	Muscular dystrophy
P9		Male	30	Muscular dystrophy
P10		Male	43	Muscular dystrophy
P11		Male	47	Muscular dystrophy
P12		Male	60	Muscular dystrophy
P13		Male	40	Muscular dystrophy
P14		Male	27	Muscular dystrophy
C1	Caregiver	Male	32	Muscular dystrophy
C2		Female	35	Muscular dystrophy
C3		Male	43	Muscular dystrophy
C4		Male	51	Muscular dystrophy
C5		Male	40	Muscular dystrophy
C6		Male	46	Muscular dystrophy
C7		Female	30	Polio
C8		Female	43	Polio
C9		Male	45	Carcinoma
C10		Male	54	Motor neuron disease
C11		Male	37	Amputee from both legs

Figure 4 shows the average and standard deviation for the feedback obtained from patients and caregivers for all the five questions. The averages and standard deviations for the patients and caregivers were found to be 3.71 ± 1.48 and 3.91 ± 1.22 for Q1, 3.28 ± 1.81 and 4.09 ± 1.04 for Q2, 3.21 ± 1.05 and 3.09 ± 0.83 for Q3, 4.64 ± 0.49 and 3.91 ± 1.04 for Q4, 3.85 ± 1.29 and 4.27 ± 1.10 for Q5, respectively. The caregivers expressed most interest (4.27 ± 1.10) in having an automated bed system for home use. The patients rated highest (4.64 ± 0.49) for the automated bed system to ease burden on caregivers.

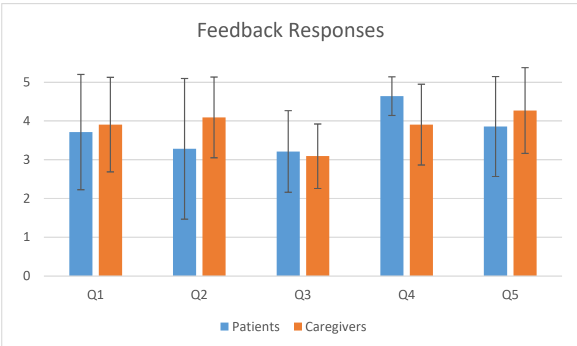

Figure 4. The feedback for five questions (Q1 to Q5) from patients and caregivers. Bars represent the Likert scale averages, while the error bars represent the standard deviations.

We observed that the muscular dystrophy patients had more severe mobility impairment and hence they required more support for repositioning than the other patients. The caregivers of muscular dystrophy patients had more burden of repositioning that also affects their own sleep and psychological well-being. All participants expressed willingness to keep the automated repositioning bed for the patients. Additional safety features, such as side rails, were suggested to be incorporated. Moreover, it was suggested that a pressure measurement system could be included to monitor the development of bedsores.

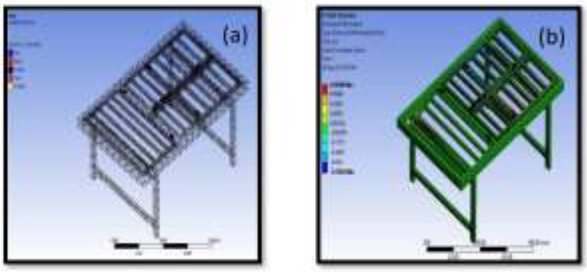

Figure 5. Strength analysis using Ansys software (a) meshing of the 3D CAD model, (b) the directional deformation where color contours indicate quantity of deformation

Simulation and Hardware

Figure 5a illustrates the precise meshing used to enhance simulation accuracy, with fine meshing applied specifically to critical load-bearing areas such as the head, foot, and lateral tilt sections of the bed, as these regions support the majority of the patient's weight. Fixed supports were assigned at the base of the pillars to simulate the bed's stability, and a -1000 Newton force was applied in the y-direction to replicate gravitational effects with an assumed 100 kg load. The deformation analysis showed minimal displacement across the bed platform, with lateral tilt positions exhibiting deformations ranging from 0.58 mm to -0.55 mm, as shown in Figure 5b.

Figure 6 illustrates the final prototype in various positions. The bed's control system regulates motor movements by continuously monitoring button presses, time intervals, and mode settings. It supports both manual and automated operation, with real-time updates displayed on the LCD to provide user feedback.

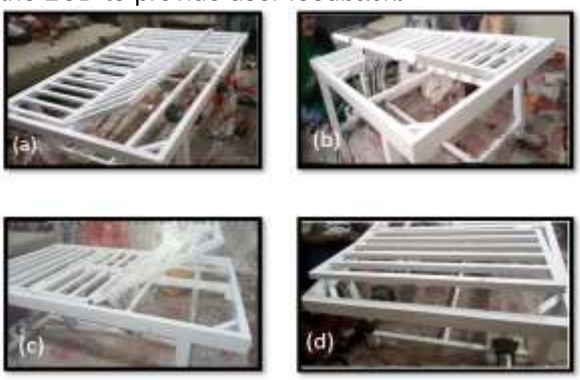

Figure 6. The final prototype in different positions, (a) right lateral tilt up, (b) left lateral tilt up (c) head up, and (d) leg up movements.

DISCUSSION

This study aimed to develop an assistive device capable of automating side-turning motions for bedridden patients in both home and hospital settings. The prototype was designed to enhance patient care by preventing pressure injuries and improving patient comfort while reducing the physical strain on caregivers.

The CAD-based design successfully demonstrated all intended movements, and finite element simulations confirmed the structural integrity of the bed. Minimal deformations were observed across the bed platform, with slight displacements in the leg section due to insufficient localized support. Under the applied force, lateral tilt positions exhibited only minor deformations, validating the design's stability [17]. Furthermore, the hardware prototype effectively translated these simulated movements into real-world functionality, offering both manual and automated repositioning options.

Feedback from patients and caregivers strongly supported the need for an automated repositioning system at home. Participants ranked highest when asked whether the system could ease the caregiver's burden, indicating that automation could significantly reduce the physical strain associated with frequent manual repositioning. Traditional repositioning methods are labour-intensive and repetitive, leading to caregiver fatigue and potential musculoskeletal injuries. By automating these movements, the system offers a practical solution that improves both patient care and caregiver well-being.

However, when asked whether the system could enable patients to reposition themselves independently, the average ranking was close to neutral, indicating uncertainty about the system's ability to enable full patient autonomy. This response suggests usability challenges, particularly for patients with severe mobility impairments who may struggle to operate the controls. While the system offers both manual and automated modes, its practicality as a fully independent repositioning tool remains limited. Future improvements, such as voice-activated controls or adaptive interfaces, could enhance accessibility and empower patients to manage their own repositioning more effectively.

The patient and caregiver feedback has identified key areas for improvement. Patients with severe mobility impairments are the most neglected population and their caregivers face various health concerns. The caregivers often experience significant burden due to the progressive nature of the diseases, leading to limitations in personal needs, financial strain, and mental health issues like anxiety and depression[18-20]. The impact on caregivers' health-related quality of life is substantial, with caregivers spending a significant amount of time managing the overall treatment and care for the affected individuals [21]. Additionally, the need for specific technological training and support for caregivers is highlighted, emphasizing the importance of assessing caregiver needs and providing individualized support to mitigate the challenges they face.

Despite its promising potential, this study has several limitations. The prototype was tested on a relatively small sample size, which may not fully capture the diverse needs of bedridden patients with varying medical conditions. Additionally, while finite element analysis confirmed the structural stability of the design, long-term durability and performance under continuous use were not extensively evaluated. The manual control system may also present challenges for patients with severe motor impairments, limiting its usability without caregiver assistance. Furthermore, the study did not explore the psychological and emotional impact of automated repositioning, which could influence patient acceptance and adoption rates. Lastly, incorporating advanced safety features such as pressure monitoring and fall detection could enhance reliability and further improve patient outcomes.

Despite the benefits of automated patient repositioning systems, several areas for improvement and research emerge from feedback and study findings. Future work can focus on integrating wearable sensors to monitor pressure distribution, ensuring optimal repositioning and reducing the risk of pressure ulcers [22,23]. Advanced user control can be implemented with machine learning and sensor fusion for automated user intention detection [24,25]. Future research should also encompass patient populations to validate effectiveness across various conditions [26,27]. Enhancements such as integrating safety features like side rails, wearable harness [28], and implementing pressure monitoring systems are crucial to enhance patient safety and comfort. Additionally, advancements in robotics can be explored to further automate patient repositioning, minimizing caregiver involvement[29-30]. Contactless repositioning systems, which use advanced sensing and actuation technologies, could also be investigated to enhance patient comfort and safety while reducing mechanical constraints [31]. These developments would improve both usability and effectiveness, bringing the system closer to state-of-the-art patient care solutions.

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Author Contributions
All authors contributed equally.

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Conflict of Interests
None.

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