A ROBOTIZED BED FOR BEDRIDDEN PATIENTS

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Abstract: Longtime bedridden patients may have serious problems from the immobilization and a reposition of their body can be often request at least to mitigate effects in pulmonary complications and pressure ulcers. This paper approaches the problem on how to give basic movements to those patients to help in those situations by permitting body repositioning through movements of bed segments. The solution is proposed in term of design of structure and control of a robotized hospital-type bed in which the bed structure is portioned in segments that are properly activated and controlled by a specific mechanism with a specific controlled operation. The proposed solution is tested and characterized via simulations whose results verify the feasibility and efficiency of the proposed solution for a future implementation in hospital frames.
Keywords: Service Robotics; Biomedical Devices; Design; Controlled Operation, Hospital Beds.

1. Introduction

Hospital beds with adjustable frames are essential assets for healthcare, offering physical support and comfort to bedridden patients grappling with complex health conditions. The recent COVID pandemic highlighted how critical these beds are, as manufacturers struggled to provide them when demand was peaking. As a result, there has been a notable increase in attention and development of hospital beds. This stems from the need to enhance patient experience and speed up recovery, with a particular focus on improving comfort, monitoring, and safety for patients forced in bed for long periods of time.

At the same time, beds have to be designed with the welfare of healthcare workers in mind. First, caring for a bedridden patient forces healthcare operators to physical strain when supporting patients to move, get up, and lay down. Furthermore, prolonged physical contact results in further exposition of healthcare operators to contagious diseases. Thus, providing hospital beds with the autonomous or remotely operated capability to physically support and assist the patient also shields healthcare workers from critical health risks.

Current hospital-type beds cater to the unique requirements of individuals facing health complications with reconfigurability (usually by offering back and/or leg support) and advanced medical and biomedical instrumentation, allowing healthcare workers to maintain a constant monitoring of patient condition. These features are especially critical in the context of Intensive Care Units (ICUs), as detailed in medical literature [1–5].

The ever-increasing pressure of an aging world population, combined with recent medical challenges, innovative technological solutions for these beds are in high demand. These systems should address the complications of prolonged bed care, such as sores, as well as provide improved physical support, comfort, and monitoring for bedridden patients. Pneumatic mattresses have already been demonstrated in facilitating patient motion, especially addressing bedsores, as explained in [1–5]; however, increasing the level of physical assistance with a large range of motion could improve patient self-sufficiency and allow medical personnel to act more promptly and efficiently thanks to remote controlled systems. Robotized hospital beds are arguably the most promising avenue, and they can incorporate elements like webcams and digital image processing to identify potential issues as early as possible and help medical operators to flag potential problems. These mechatronic designs offer innovative approaches to patient care and medical operator safety, as exemplified in recent works [6–10]. However, most research on robotized hospital beds has focused on the sensing and control aspects, without increasing the level of physical assistance provided by the bed.

In this paper, we address this research and technological gap by presenting a new hospital bed design that provides further mobility thanks to a segmented design. Existing reconfigurable/robotized beds generally offer only one or two degrees of freedom: they are able to recline the upper part of the bed, to offer back support and let a bedridden patient sit up for eating, and they sometimes offer leg support, lifting patient's feet with articulated parallelogram lifting mechanisms. Notably, this kind of support only acts in the sagittal (lateral/longitudinal) plane. With the novel design here proposed, based on the concept first presented in [1, 5, 11], bed mobility is expanded to the coronal (frontal) plane as well, as this segmented bed can help a patient move from the left side of the bed to the right one, or vice versa. This action not only provides extra motion to avoid bed sores, but also supports the patient standing up or reaching the opposite side of the bed.

This robotic bed is here presented with a new mechanical design, based on a four-bar linkage mechanism with an external linear actuator to motorize each segment while keeping it extremely compact and embeddable in the main bed frame. The mechanical behavior of each segment is analyzed with its main kinematic and dynamic characteristics to ensure the adequate functioning of the system in medical scenarios. This validates the usage of the proposed bed segment in combination with state-of-the-art control and sensing systems to improve the status, comfort, and assistance of the imbedded patient.

2. Materials and Methods

Robotized hospital beds are particularly effective in Intensive Care Units (ICUs), as they cater to patients with complex health conditions requiring specialized care. In these settings, patients often rely on special biomedical devices for continuous monitoring of vital signs and additional devices to address unique complications.

The specific challenges faced by bedridden patients include two primary complications: stationary lung secretions and the development of pressure sores, as depicted in Fig. 1. Prolonged immobility and the sedation of cough reflex due to extended bed stays can lead to the accumulation of secretions in the lower lobes of the pulmonary complex. This issue has prompted healthcare professionals to keep patients prone, particularly during the treatment of COVID-19 patients [12], despite the associated discomfort. However, implementing cyclical semi-rotational movement along the patient's axial (transverse) plane can effectively counteract mucus buildup and the subsequent risk of lung atelectasis.

Pressure ulcers are also a common issue in bedridden patients. These sores result from applied pressure, friction, or shear, as highlighted in [13, 14]. They not only harm the skin and nearby tissues but also pose infection risks, endangering patients' lives. Preventing such sores involves turning patients every two hours, a practice that exposes healthcare workers to the risk of repetitive physical exertion as well as potential contagion from sick patients [13, 14].

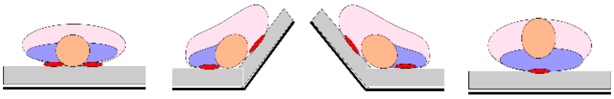


Figure 1. A graphical representation of a bedridden patient subject to cyclical motion to avoid lung secretion and pressure sores. The effects of prolonged bedridden conditions are here represented in brown for pulmonary secretions and yellow for pressure sores (decubitus).

2.1. Requirements

Figure 2 provides an overview of the specific considerations and prerequisites for designing a robotic bed solution tailored to the needs of bedridden patients. While the figure focuses on the aforementioned clinical complications, these design elements can also be extended to patients suffering from other conditions that impose prolonged bed stays. The characteristics in Fig. 2 outline the main factors that affect the design and functionality of a robotic bed, particularly in terms of mobility, structure, and sensor integration, all aimed at addressing the primary challenges faced by bedridden patients.

When addressing motion capabilities, the key requirement is the desired range of motion for each bed segment, ensuring precise motion resolution without reaching an excessive speed that could potentially harm the patient. Whereas previous design solutions for bedsores use pneumatics, an improved level of motion control is attainable only by using electric motors with encoders, even with open-loop algorithms. Electric motors can also enable vibratory movements, introducing controlled biomechanical stresses that can enhance the efficiency of drainage procedures and increasing the overall therapeutic effectiveness of the bed. Overall, the integration of position- or velocity-controlled servomotors offers a valuable advantage, enabling programmable motion sequences that medical professionals can tailor to the needs and prescribed therapies of individual patients. This programmability extends to remote operation, enhancing the bed's versatility.

For an actuation solution that is at the same time efficient and compact, a lightweight foldable linkage mechanism can achieve optimal performance for the bed's structure. To provide patients with physical assistance, the payload of each segment needs to be enough to lift segment mass, the respective segment of mattress/topper, and the body mass of the patient. For a bed with six segments, this payload has been estimated to be around 50kg per segment, applied to the center of the segment itself. While this payload is deemed sufficient in this work, different designs and architectures could require a reevaluation of this requirement. A compact mechanism design can also provide the bed with enough space underneath to allocate a battery unit, which could provide power to facilitate the bed's operation in locations without readily accessible power sockets (e.g, during ambulance transportation), ensuring uninterrupted functionality for an extended duration.

Structure	Motion	Sensing
- Size	- Joint range	- IMUs
- Weight	- Resolution	- Force sensors
- Mobility	- Speed	- EMG signals
- Cleanliness	- Payload	- Temperature
- Power	- Planning	- Blood pressure

Operation
Safety; comfort; portability; user-friendliness; affordability

Fig. 2. A summary of requirements for robotized hospital beds.

Regarding the bed's structural design, as summarized in Fig. 2, the conventional hospital bed frame is here adapted by introducing segmentations to enable patient mobility along multiple axes. In addition to conventional design considerations, particular attention needs to be paid to the strict requirements related to sanitation and cleanliness, aligning with medical sanitation protocols. As such, the proposed design should facilitate cleaning and sanitizing operations, and generally be hygiene oriented.

Depending on the bed's target location, energy efficiency could be a critical concern: when medical equipment might be sensitive to interference, the power consumption of the bed must be kept to the minimum. This also ensures a better functioning when operated through battery, in addition to minimizing electromagnetic emissions.

In addition to the specific sensors required for patient monitoring, the proposed robotized bed would benefit from specific ones aimed at achieving accurate and/or closed-loop control, as well as further sensors aimed at monitoring and controlling the effects of bed motion on the patient's status. Inertial Measurement Units (IMUs) and pressure sensors can be combined, for example, to identify the position of the patient and the bed configuration at the same time. Further medical sensors can be integrated to the bed segments and mattress sections to monitor vital signs such as temperature, blood pressure, and other relevant parameters, and analyze their potential correlation with bed motion sequences. Electromyography (EMG) sensors can also be used to assess the musculoskeletal response of patients to bed movements.

Finally, the bed must meet safety and comfort standards dictated by medical protocols. To enable a quick technology transfer to hospitals, the bed's functionality should be user-friendly, allowing medical operators and hospital staff to manage it without complications and at a limited cost.

2.2. Robotized Bed Design

The proposed design for a robotic bed represents an evolution from the previous concept [1, 11], which focused on the needs of the COVID pandemic. The new design increases the number of independent segments to six, improves the efficiency of the actuation mechanism with a new linkage design, as adds mobility on the sagittal plane (back support and leg lifting), as illustrated in the models in Fig. 3.

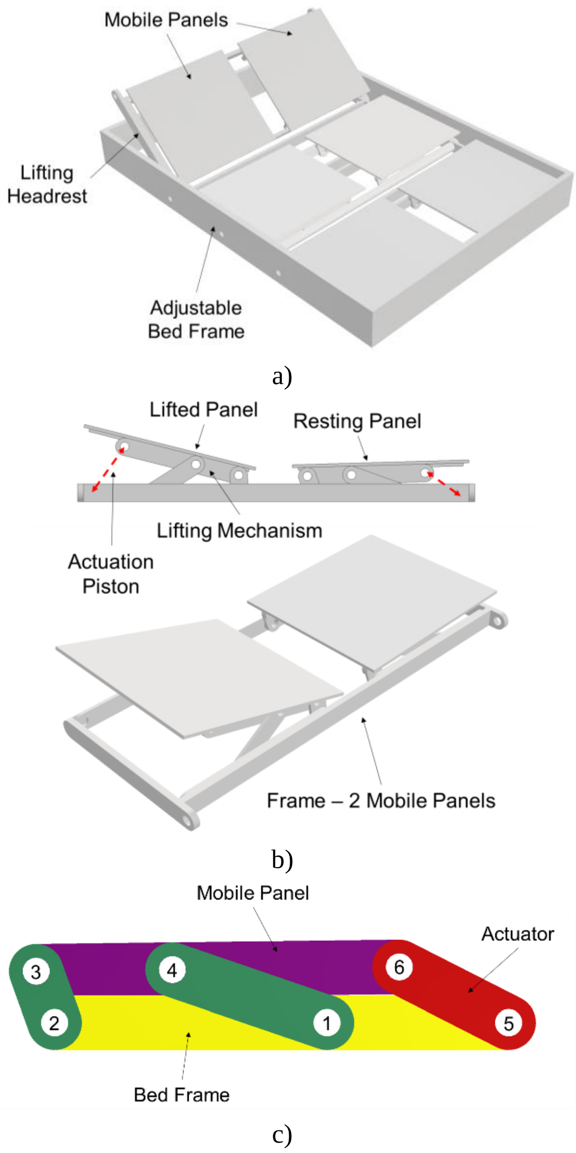


Fig. 3. A 3D CAD model of a robotized bed mechanism for bedridden patients: a) Overall bed design; b) Details of two reconfigurable segments; c) Actuating mechanism in a folded configuration.

In Fig. 3a, a model of the whole bed shows the adjustable frame (with the headrest lifted for back support) and the layout with six reconfigurable panels. A single set of panels is shown in Fig. 3b, where it is possible to observe the four-bar linkage that constrains bed motion in both a closed (on the right) and open (on the left) configuration. This mechanism has been selected as fully foldable and compact, as it can integrate not only the mechanism itself but also a linear actuator (that acts on the distance indicated by the red segmented arrow in Fig. 3b) without increasing overall volume for the module.

A detailed view of the mechanism is shown in Fig. 3c, where the connection between the mobile panel of the bed segment and the fixed bed frame is clearly shown with the three connecting links (two passive, with a RR kinematic chain, in green, and an active one with an RPR kinematic chain in red). The base revolute joints of the passive links are 1 e 2, while 3 and 4 identify their mobile ones. Similarly, the active link is fixed to the frame in point 5 and to the mobile platform in point 6. Figure 3c, by illustrating the fully folded configuration, also clearly demonstrates the compactness of the proposed mechanism. This 1-dof system provides the primary function of lateral rotation according to the scheme in Fig. 1. The patient's torso can be rotated cyclically by a pair of right-left segments, as illustrated in Fig. 3b, with the corresponding head and leg segment providing additional support when needed.

The motion control system can be designed with a proper PI algorithm according to the conceptual design in Fig. 4 using sensors in bed segments and patient body for bed motion and medical monitoring with central role of the control unit. Considering the proposed robotized hospital bed with two upper-part segments, movements can be carried out to allow the mobilization of a bedridden patient as controlled by sensors with data from the patient, the segments of the bed, the mechanism and the actuators. A PI control can be conveniently used to operate the slow motion of a bed segment with its proper positioning.

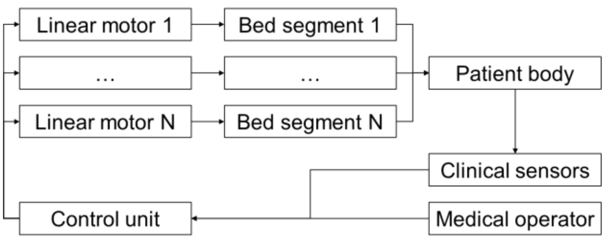


Fig. 4. A conceptual design of a robotic bed design for bedridden patients

2.3 Robotized Bed Operation

The design illustrated in the previous section functions accordingly to the scheme in Fig. 4. Its motion control system can be used in open loop with monitoring provided by a healthcare operator, given the low operational speed and no need for high motion accuracy. However, a closed-loop scheme makes remote operation safe as well, and it could be achieved by implementing a proper PID algorithm according to the scheme in Fig. 5, feeding back to the central control unit information acquired by the sensors in bed segments or worn by the patient. The synergic implementation of the controller and the mechanical design should be carefully studied to meet the motion and payload requirements discussed in 2.1.

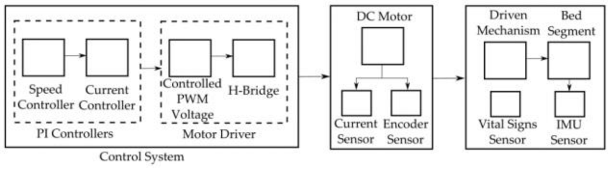


Fig. 5. An example of a closed-loop control stratgy for the proposed bed.

3. Results and Discussion

Given the requirements discussed in section 2.1 and the proposed bed design reported in section 2.2, numerical simulations have been run to validate the proposed mechanism design for a robotized bed. In particular, the lifting mechanism in Fig. 3c has been tested with a payload of 50kg (500 N) applied to the center of mass of the segment.

The driving mechanism in Fig. 3c has been analyzed with a dynamic simulation on Autodesk Inventor Pro 2024 (lumped mass model, Newton-Euler solver) on the exemplary motion in Fig. 7. The segment has been assembled with joint constraints and material set to steel for all rigid links, to ensure mechanism strength. Motion has been imposed through the actuator to lift the segment up to a desired height, imposing a cubic motion law for a smooth motion (shown in Fig. 8, with no discontinuities in acceleration and jerk) to ensure patient comfort. Simulation time has been set to 5 seconds; actual operational times for the bed are actually higher (resulting in a slower motion and lower inertial effects), and by setting it to 5 seconds the simulation already provides a worst-case scenario to ensure an in-built safety factor in the numerical results.

Figure 9 illustrates simulation results in terms of actuation force and power consumption, computed as the product between actuation force and velocity of the active joint. These values are needed to properly dimension the system, providing information on the maximum force at the actuator (600N) and the overall power consumption to size the power supply (less than 12W). In order to ensure a force of 600N, the gearbox of the linear actuator will need to be sized accordingly. The power supply will need to provide 12W per segment, resulting in an overall 72W maximum estimated power consumption when operating all six segments simultaneously. Realistically, however, the weight of the person will be moved by the segments on one side only at any given time, halving the estimated power consumption peak to 36W.

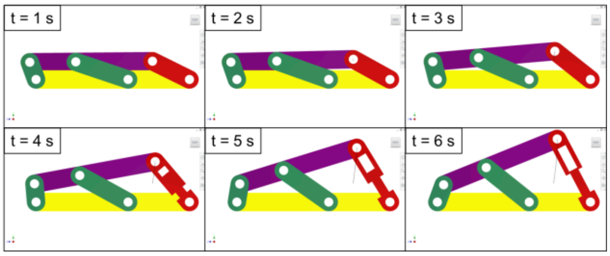


Fig. 7. Snapshots from a dynamic simulation of the segment lifting mechanism.

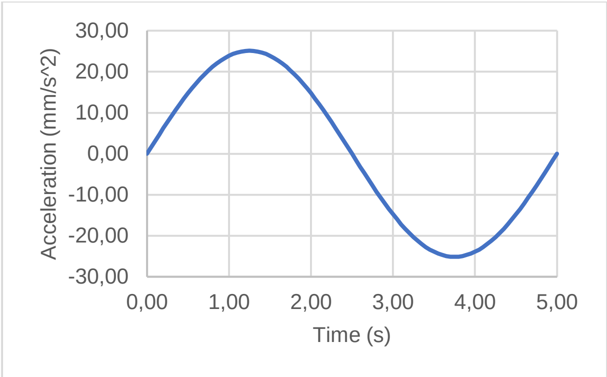
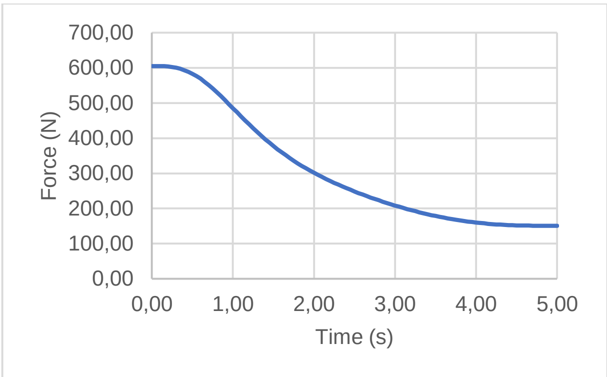


Fig. 8. Imposed motion law in terms of linear acceleration of the active prismatic joint.



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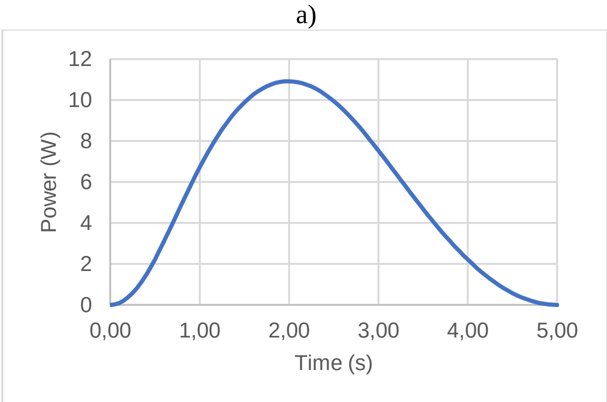
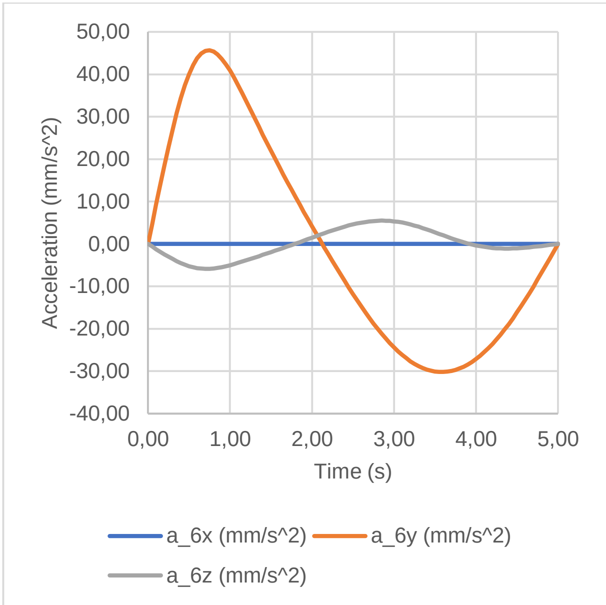


b)

Fig. 9. Simulation results in terms of actuation: a. Resulting actuation force; b. Resulting power consumption.

The bed is further characterized in terms of acceleration of the segment, shown in Fig. 10a, and reaction force at the passive revolute joint of the mechanism of Fig. 3a, illustrated in Fig. 10b. Segment acceleration, in Fig. 10a, is shown to be smooth and without discontinuities, ensuring a safe and comfortable experience for the patient and avoiding any risk of harming them with sudden motion. Joint reaction forces, in Fig. 10b, can be used as a design tool to dimension bearings; with a maximum force lower than 800N, the proposed operation does not strain excessively any of the joints, safeguarding structural integrity.



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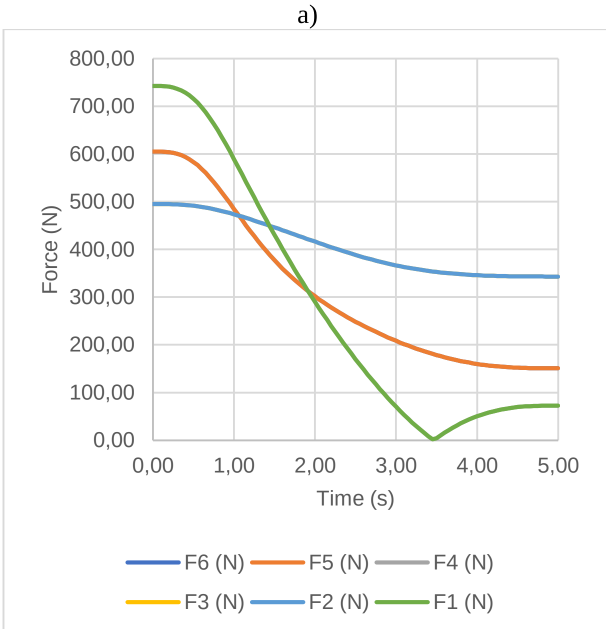

b)

Fig. 10. Computed results of the simulation in Fig. 7: a) Acceleration of the segment, computed at the central point of joint 6; b) Reaction forces at the passive revolute joints.

6. Conclusions

Conditions and effects of bedridden patients are analyzed to identify characteristics and requirements for design and operation of robotized hospital-type beds for patients who, being immobilized for long time, suffer pulmonary complications and pressure ulcers. The proposed robotized bed solution is designed with a structure and control for a proper bed motion that can help the bedridden patients as also supervised by healthcare operators though a programmed and remote interaction. The designed bed control is characterized with simulation results to validate the soundness of the mechanical design and the fairly simple motion control low for a slow-speed movements of the actuated bed segments. The proposed solution can be convenient also in the treatment of COVID patients in intensive care units as an application of a fully programmed operation of the bed segment movements outlined by exploiting functionality and characteristics of the proposed robotized bed.

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